Saskatchewan
Energy and Mines
Saskatchewan
Geological Survey

Mineral Resources of Saskatchewan

Miscellaneous Report 91-5

1991

Printed under the authority of the
Minister of Energy and Mines

91-05241/

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Cover: depicting some of the Province's mineral resources and related activities. From left to right - *Top row*: uranium ore; Deilman open pit, Key Lake uranium mine; *Second row*: first gold brick being poured at Star Lake gold mine; aerial view of Star Lake gold mine; Flin Flon mine and smelter which has produced copper and zinc since 1930. *Third row*: oil field pumping stations; circular cutting marks of potash mining machines at Esterhazy; conveyer belt carrying potash away from the working face. *Bottom row*: drag-line operating in stock-piled sodium sulphate at Ormiston Sulphate Mine; coal handling facility at Bien Fait mine of Estevan Coal Corp.; drag-line open pit coal mining near Estevan.

Parts of this report may be quoted if credit is given. It is recommended that reference to this report be made as follows:

Mineral Resources of Saskatchewan (1991): Sask. Energy Mines, Misc. Rep. 91-5, 76p.

Updated and reprinted from CIM Directory, 1987

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Released May 1991
Saskatchewan Geological Survey

Foreword

This report is based essentially on the September 1987 CIM Directory feature article "Saskatchewan's Mineral Industry: Past and Present" and is reprinted with permission of The Canadian Institute of Mining and Metallurgy.

The Department of Energy and Mines wishes to thank Mrs. Pearla Gantz (Editor) and Mrs. F. Ballard (Editorial Assistant) of the Canadian Institute of Mining and Metallurgy for their helpfulness in providing plate negatives and other materials relating to the original, and for facilitating the Institute's approval to republish the report.

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This edition was produced by desktop publishing software and laser printer under the direction of D. MacDougall (coordinator), C.T. Harper (production editor) and N. Richmond-Johnson (desktop publishing).

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April 1991

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Introduction

This paper provides overviews of (a) the progress of mineral exploration from the early years to the present, (b) the geology of the province as a backdrop to the mineral industry, and (c) the current status of the industry in its various components. Emphasis is on the metallic and industrial minerals, although petroleum forms part of the historical review.

Saskatchewan is effectively divided into a northern setting of deformed Precambrian basement and undeformed Athabasca sedimentary rocks, and a southern region of sedimentary strata ranging from Cambrian to Tertiary. This dichotomy determines the distribution of mineral industry and related government activities. Thus, the metallic mineral environment is northern and the nonmetallics, as well as petroleum and natural gas, are southern. Saskatchewan is endowed with inland oil reserves second only to Alberta's, natural gas third to Alberta's and British Columbia's, potash, sodium sulphate and uranium second to none in Canada, and significant coal reserves. These resources support industries made up of companies ranging from the internationals to self-incorporated individuals.

The gold play has come to Saskatchewan, as it has elsewhere. Deposits which have lain undeveloped for 50 years and more because of small size are now the focus of intense exploration and evaluation. The drive to develop this resource and find new deposits has been propelled by a combination of prospecting perseverance, investment flow-through funding and favourable economics. An additional stimulant has been the focussed mapping program delivered by the Saskatchewan Geological Survey and the Geological Survey of Canada, working together under the Canada-Saskatchewan Mineral Development Agreement, 1984-1989. In the past few years, Saskatchewan has seen the opening of three gold mines in the La Ronge Belt (Star Lake, Jolu and Jasper) and the imminent development of two more (Contact Lake and Seabee), the discovery of a significant base metal deposit in the Hanson Lake Block (McIlvenna Bay), another major uranium deposit (McArthur River, P2 North), and the finding of two clusters of diamondiferous kimberlite pipes at Sturgeon Lake and Fort-a-la-Corne.

The value of mineral sales in Saskatchewan in 1989 stood at $2.93 billion, of which petroleum and natural gas contributed $1.45 billion, potash $882 million, uranium $380 million, coal $99.6 million, sodium sulphate $23 million and salt $19.9 million. The total value of mineral production represented 6.2% of the Gross Domestic Product in 1989, compared to 9.8% for agriculture, the other major primary industry.

Saskatchewan ranked fourth overall in total value of 1989 Canadian mineral production including petroleum and natural gas ($3 billion), after Alberta ($16.2 billion), Ontario ($7.3 billion) and British Columbia ($4.1 billion). Excluding petroleum and natural gas, Saskatchewan is in fifth place with total value of production ($1.48 billion) after Ontario ($7.2 billion), British Columbia ($3.3 billion), Quebec ($2.8 billion), and Manitoba ($1.6 billion).

History of Mineral Exploration and Development

Base and Precious Metals

The search for metallic minerals in Saskatchewan began in about 1859 following the discovery of gold in the North Saskatchewan River. Dr. James Hector of the Palliser expedition, in the vicinity of Edmonton in that year, observed a "few specimens of gold being worked out". Apparently the gold was discovered by prospectors enroute to the Cariboo gold rush in interior British Columbia. Much of the activity on the river was centred around Edmonton, but flour gold was found all the way downstream to Prince Albert. Small-scale placer mining has been taking place ever since.

Mineral exploration in the Precambrian Shield followed mapping by the Geological Survey of Canada. During 1882-93, J.B. Tyrrell and his assistant, D.B. Dowling, surveyed many of the major waterways. Of particular interest to later explorers was recognition of noritic rocks on the north shore of Pine Channel at the east end of Lake Athabasca (Figure 1). In 1896, Tyrrell returned to Saskatchewan and made a further survey in the Flin Flon area, noting the presence of quartz veins on Amisk Lake. Later these would prove significant. W. McInnes worked in the province in 1908-10, investigating the geology of the Shield edge area between Lac La Ronge and the Manitoba border. He reported copper sulphides at Moose Point on the northwest shore of Lac La Ronge, at a location which would become, in 1966, the site of the Anglo-Rouyn copper mine.

A miner named Dalton supposedly made the first gold discovery in the Shield, in 1910, north of Pine Channel. A short tunnel was driven with disappointing results and, although many claims were staked in the vicinity between 1910 and 1913 and sulphides were encountered, there was no further mention of gold.

The first significant gold discovery occurred three years later. Prospectors Thomas Creighton, Jack Mosher and Leon Dion, working for Toronto entrepreneur and one time prize-fighter Jack Hammell, found a gold-bearing quartz vein on the northwest shore of Amisk Lake. The prospect subsequently became the Prince Albert (Monarch) Mine, named after the town in which the development capital was raised. It was mined in 1937 and again from 1940-1942.

The discovery concentrated interest in the area and numerous other gold prospects were found, including the Graham Mine and those at Robinson Creek, Waverly Island and Mosher Lake. More importantly, in 1915, Thomas Creighton and the Mosher and Dion brothers chanced upon the massive sulphide copper-zinc deposit which became the Flin Flon Mine. This discovery resulted in a change in emphasis, to base metal prospecting, and that same summer the Mandy high-grade copper deposit was found in Manitoba, a short distance to the south, on Schist Lake. The Mandy produced initially from 1917 to 1920, although only the highest grade copper ore could be mined economically because of the cost of hauling the ore by horse drawn sleigh, barge and train to the Trail smelter in southern British Columbia. The Flin Flon deposit would wait until 1931 for the first production by the Hudson Bay Mining and Smelting Company Ltd., because the ore was not of sufficiently high grade to ship without concentration of the copper and zinc sulphides. The metallurgical problems of separating these economic minerals from the dominant pyrite would not be solved until 1927. Power for the operation was and continues to be provided by a hydroelectric plant constructed on the Churchill River, at Island Falls, some 100 km to the north. The main orebody was exhausted in 1989 after nearly sixty years of production.

At about the time the Flin Flon deposit was found, exploration for nickel was initiated in the eastern part of Lake Athabasca by H.V. Dardier, sponsored by the British armaments firm of Vickers. The exploration was stimulated by Tyrrell's report of noritic rocks which were recognized, by analogy with Sudbury, to be a potential host to nickel mineralization. Two Davis-calyx steam-powered shot drills were initially used for sampling. Parts from these drills are now preserved in the Western Development Museum in Saskatoon. The expedition, in reality, was a failure, although the subsequent discovery in 1928 by Dominion Explorers of a small low-grade, copper-nickel deposit at nearby Axis Lake suggests it was justified.

In 1926, the first traces of gold were reported from the La Ronge area, in fact from the Moose Point copper showing originally identified by McInnes and also from the Sulphide Lake area farther north. Two years later, another significant discovery was staked at Rottenstone Lake by trappers Tremblay and Olson, likely working from information supplied by local Indians. This property was acquired by Richard Hall, M.L.A. for Cumberland, and his brother, who optioned it to Cominco. The deposit marked by a hill of 'rotten gossanous rock' assayed high in nickel, platinum and other precious metals. It was drilled by Cominco and found to be small and uneconomic.

The thirties to the mid-forties saw significant gold exploration, particularly in the Flin Flon area, where a number of small gold mines, notably the Henning-Maloney, Graham, Monarch and Douglas Lake (Newcor), yielded minor production. Several gold prospects were identified in the belt of metavolcanic rocks stretching northeast from La Ronge (La Ronge Belt), especially in and around Sulphide Lake, from which there was also a small amount of production. This occurred at the Preview and Pap Lake prospects and from discoveries made by local prospector Adolph Studer. There was considerable exploration north of Pine Channel and several showings of gold were also found there.

More significant, however, was the recognition in 1934 of gold mineralization on the north shore of Lake Athabasca, between Lodge and Neiman Bays. Prospectors Tom Box and Gus Nyman made the discovery, which precipitated a major gold rush and establishment

Figure 1 - Location map and mineral deposits

of the town of Goldfields. The Box property was optioned to Cominco, who by 1935 had begun underground work and by 1937 had plans in place for mill construction. Power for the operation was supplied by a hydroelectric plant built at Wellington Lake, some 55 km away. Meanwhile, two other prospects, the Athona and Frontier, which were never producers, were undergoing underground development and the town of Goldfield had grown to 1000 people. The Box Mine began production in 1939 and shut down in 1942 because of the low ore grade. The town of Goldfields died with it.

Stemming from the gold rush around Goldfields was an event which was to change the face of mineral exploration in Saskatchewan. In 1935, prospectors of the Mineral Locators Syndicate identified pitchblende at the Nicholson property, 3 km east of Goldfields. The prospectors were familiar with the mineral by virtue of their experience at the Port Radium radium mine on Great Bear Lake. Samples were collected by Geological Survey of Canada geologist F.J. Alcock and positively identified as pitchblende by Survey mineralogist H.V. Ellsworth. Alcock reported this discovery in his 1936 report, "The Geology of the Athabaska Region". As a result of the discovery, from 1945 until the present day,

uranium exploration has often predominanted over that for other metals.

During the years following World War II, the search for other metals continued and was aided by an ongoing mapping program conducted by the newly formed Saskatchewan Geological Survey, incorporated in 1947 in the Mineral Resources Branch of the Department of Natural Resources. Over the years that followed, the provincial government became additionally involved through the provision of incentives and direct assistance to prospectors. The introduction of newly developed airborne geophysical surveys by both industry and government opened up in northern Saskatchewan, as elsewhere, a much larger area to exploration.

The postwar years proved to be a period in which base metal exploration and development thrived, whereas gold activity faltered largely because of the fixed gold price of US $35/oz. Irrespective of this, several important gold discoveries were made, for the most part in the La Ronge Belt, particularly by prospector Eric Partridge and prospectors working for Cominco who remained active after closure of the Box Mine. Partridge's discoveries included the Kaslo near Tower Lake (1958), the Komis at Waddy Lake (1958) and the Kahn veins at Star Lake (1961), whereas Cominco prospectors found Weedy Lake (1948) and the Seabee at Laonil Lake (1949). Although these and other previously discovered prospects were examined by trenching and some drilling, it was not until the eighties that they would be subjected to intensive exploration.

As for base metals, some prospects found before World War II were reactivated and new discoveries were made. Among the former was the Anglo-Rouyn Mine, at the site of the copper prospect noted by McInnes and later staked by the Hall brothers in 1915. The mine produced essentially copper, but the ore was significantly endowed with gold and silver. It operated between 1966 and 1972. Concentrate was shipped via the Hanson Lake road to the Flin Flon smelter. The Rottenstone deposit was also mined at this time (1965-68). It was a small but successful producer of nickel, copper, platinum and palladium, together with some silver and gold. Operation was seasonal, with mining and milling in the summer and shipping in the winter. Concentrate was shipped to Sudbury for refining.

Several ore deposits were found in the immediate Flin Flon area and developed as essentially copper-producing satellite mines to the main Flin Flon Mine of Hudson Bay Mining and Smelting Ltd. Of these, the Flexar and Birch Lake mines were both discovered by Flin Flon prospector Joe Brain in 1941 and 1949, respectively. The former produced between 1969 and 1972 and the latter between 1951 and 1957. The Coronation Mine was a third base metal discovery developed in the area during this period. This success followed from the saturation geophysics approach to exploration pioneered for Hudson Bay Mining and Smelting Ltd. by Albert Koffman and responsible for many of the company's successes in Manitoba. Staked in 1952, the property produced between 1960 and 1965.

Some 65 km west of Flin Flon, Parrex Mining Syndicate were to find, in 1957, a small tonnage but high-grade lead-zinc-silver deposit beneath Hanson Lake. This subsequently became, in 1967, the Western Nuclear Mine; however, the orebody did not meet expectations and the mine closed in 1969 due to exhaustion of the ore.

Other areas of the Shield aside from that surrounding Flin Flon were showing some potential. Several subeconomic (to date) discoveries were made in the La Ronge Belt at Brabant Lake (zinc-copper), Nemeiben Lake and Gochager Lake (nickel-copper) and Borys Lake (zinc-lead) between 1944 and 1965. In addition, a new metallogenic province was being identified in the fifties and sixties in the well-defined 500 km long belt of metasediments (Wollaston Belt) stretching from Sandfly Lake on the Churchill River through Wollaston Lake into northwestern Manitoba. In that much of the belt is covered by glacial drift, exploration involved prospecting for mineralized boulders and tracing these back to their source by identification of boulder trains. Prospector Eric Partridge and geologist Murray Pyke deserve special mention for their contribution to this effort.

The first base metal mineralization in the Wollaston Belt was found in 1953 during the search for uranium in the Foster Lakes area. Simon Eninew, a prospector working for Partridge, found a large boulder of meta-arkose, with "copper stain but no copper", south of Juno Lake near the Wathaman River. It assayed over 2 percent copper in the form of chalcocite. Other boulders and one frost-heaved outcrop with copper mineralization were discovered in 1962 by Partridge and Falconbridge Nickel Mines. More spectacular was the discovery of the Wathaman River Boulder, which was a quartzite, containing galena and assaying an impressive 16 percent lead. It precipitated a search for quartzite-hosted lead-zinc mineralization in the area 'up ice' and in 1966 the George Lake zinc-lead deposit, some 65 km to the north, was drilled. Other discoveries of quartzite-hosted lead-zinc mineralization followed in the late-sixties at Johnston Lake and Sito Lake among other locations. While Falconbridge was active at George Lake, Great Plains Development Ltd. commenced a prospecting program in the vicinity of the original copper discoveries and was successful in identifying several other prospects. However, neither these nor the lead-zinc discoveries have yet proven to be economic.

Through the boom years of exploration for uranium in the seventies and the low metal prices of the eighties, base metal exploration stagnated, with activity essentially restricted to the Flin Flon area and the Shield edge to the west. In 1982, a significant copper-zinc discovery was made at Bigstone Lake, 90 km west of Flin Flon, by Granges Exploration AB. The deposit subcropped below 40 m of Paleozoic rocks overlying the Shield. Hudson Bay Exploration and Development Ltd., in 1985, identified the economic copper-zinc Callinan zone on strike with the Flin Flon orebody and straddling the Saskatchewan-Manitoba border some 3 km north of Flin Flon. Successes by Granges and Hudson Bay were also recorded just across the border with drilling, in 1975, of the Trout Lake copper-zinc deposit and, in 1984, of the Namew Lake nickel-copper deposit. Most

important however for the province has been the 1988 discovery, by a Cameco - Esso Minerals Canada Ltd. - Tri Gold Industries Inc. joint venture, of the McIlvenna Bay zinc-copper deposit. The deposit which subcrops beneath Paleozoic rocks is located 5 km south of the old Western Nuclear Mine at Hanson Lake. With over ten million tonnes of reserves identified from surface, it is possibly the most significant base metal discovery in the Flin Flon area since the Flin Flon orebody was found in 1913.

Gold exploration stagnated in the seventies. One short-lived attempt at gold production by Decade Development Ltd. occurred in 1974-76 at the Mallard Lake Mine, 120 km northeast of La Ronge. The prospect, named the Jolu, had been discovered and drilled by Cominco in 1944. Whereas the operation proved relatively fruitless, it served to focus interest on the area in later years.

Revitalization of exploration occurred with the surge in gold price of 1975-80 and expenditures followed a nation wide upward trend, reaching $55 million in 1988 (Figure 2). Thus, while the price of gold declined from the peak of 1980, the gold exploration boom continued, fuelled by low prices for other commodities and in Canada in particular by a favourable investment climate created by 'flow through financing'. This exploration phase has led primarily to re-examination and upgrading of historically known showings, for the most part in the La Ronge Belt, but also around Flin Flon. New deposits, such as the Star Lake 21, Rod (Jolu), Jasper and Bakos have also been found. In 1987, Saskatchewan Mining and Development Corporation (now Cameco) brought the first of these, the Star Lake (21 zone) Mine discovered in 1983, into production. It was mined out by mid-1989 after producing 76,947 oz. of gold. The Jolu Mine operated by Corona Corporation started up in November 1988, and will be depleted by 1991 and the Jasper Mine operated by Cameco, which currently has reserves to support two years of production, opened in April 1990. The Bakos deposit has yet to be developed. It is located about 40 km north of La Ronge in the Sulphide Lake gold camp. With reserves in excess of 1.5 million tonnes, the deposit is significantly larger than others mined to date in the La Ronge Belt. To the east of the Belt at Laonil Lake, the historically known Seabee deposit has been re-evaluated, and is being prepared for a start-up to mining in 1991, by Claude Resources Inc., a Saskatchewan junior mining company. In the Flin Flon area the Rio deposit originally discovered in 1936 has been subject to two short-lived attempts, in 1984 and 1988-89 at commercial production and is presently shut down. The nearby Laurel Lake gold-silver deposit on Missi Island of Amisk Lake has also been evaluated underground and deemed by operator Cameco to be subeconomic at current gold prices.

Several other properties are in an advanced stage of exploration and there seems little doubt that historical prospects will continue to be upgraded and new ones found, not only in the La Ronge "Gold" Belt but also in other areas.

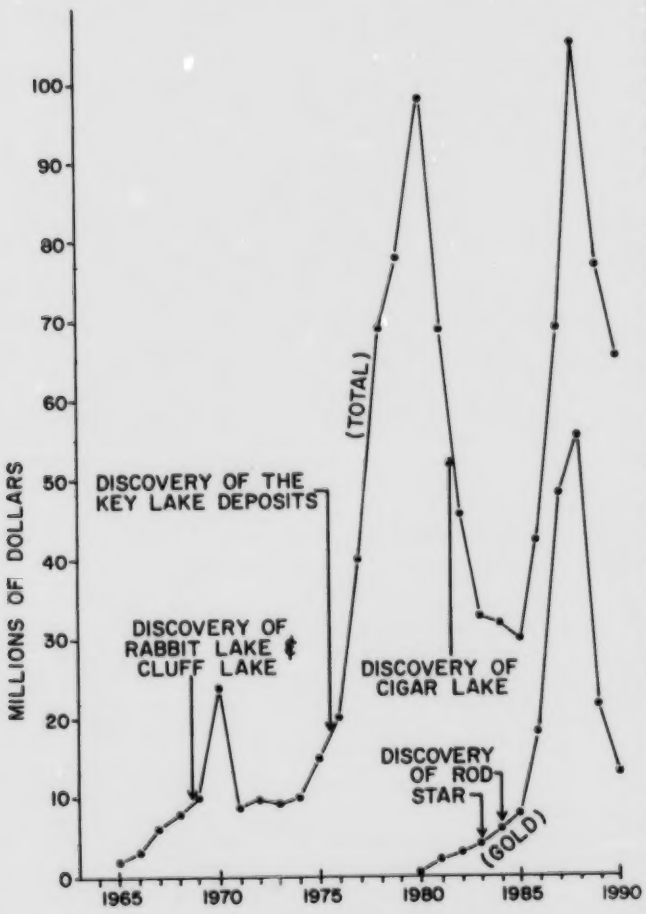


Figure 2 - Exploration expenditures for the period 1965-1990.

Uranium Exploration, 1944-1990

Recognition of the military significance of uranium led, in 1942, to reopening, at the request of the Federal Government, of Eldorado Gold Mines Ltd. radium mine at Port Radium, Great Bear Lake, Northwest Territories and radium refinery at Port Hope in Ontario. However, the objective was to mine and process uranium. At this time the company was renamed Eldorado Mining and Refining Ltd. There followed, in 1943, a ban on the staking and mining of radioactive minerals by the private sector and, in 1944, expropriation of Eldorado by the Federal Government. Eldorado, as a Crown Corporation, held the sole exploration rights for radioactive minerals and that year began an intensive effort to find and develop new sources of uranium. The Great Bear Lake deposit, the Nicholson occurrence on the north shore of Lake Athabasca and an unconfirmed occurrence near Lake Superior were then the only known locations of uranium minerals in Canada. Eldorado was assisted by the Geological Survey of Canada and, in September 1944, R. Murphy, exploration manager of Eldorado, and A. W. Joliffe of the Geological

Survey examined the Nicholson showing and recommended prospecting and staking in the area.

Using geiger counters, prospectors found over 1000 pitchblende showings during the 1945 field season, in what became known as the Beaverlodge region, and the town of Goldfields was reactivated. On September 27, 1946, Philip St. Louis discovered pitchblende at Ace Lake near a well-expressed fault. Subsequent development of this showing led to definition of the Ace and Fay orebodies.

The settlement of Beaverlodge, Eldorado's base, became established in 1949 and the town of Uranium City in 1952. After extensive diamond-drilling and the sinking of the Ace shaft, plans for production from the Ace - Fay orebodies were announced in March 1949 and subsequently realized in 1953. Electric power for this development was obtained from the Wellington Lake hydroelectric plant, installed by Cominco in 1939 to service the Box Mine at Goldfields.

In 1948, lifting of the ban on private staking resulted in considerable exploration in the area, which continued until 1958. The most significant discovery of this era was made by veteran prospectors Walter Blair and Albert Zeemel, working for Gilbert Labine, then President of Gunnar Gold Mines. Radioactive boulders found in muskeg on the south end of Crackingstone Peninsula subsequently led to the Gunnar deposit.

The boom years yielded underground exploration of 36 deposits, production from 15 main deposits and construction of three separate milling facilities. The Eldorado and Gunnar mills were supplied with ore from their own deposits, although Eldorado also undertook some custom milling. The Lorado mill relied mostly on custom ore.

By 1958, it became clear that world demand for uranium would fall, because of slow development of the nuclear power program in the United States and failure of that country to renew long term sales contracts. By 1964, Eldorado remained the only uranium producer in Saskatchewan; surviving with the aid of a federal subsidy and stockpiling program and by reducing production capacity.

The low ebb of mineral exploration induced the Saskatchewan Government to introduce a financial assistance program to companies with approved exploration work schedules. In 1967, a consortium named the Dynamic Group, taking advantage of this program, undertook to fly a systematic radiometric survey of the unexplored Athabasca Sandstone Basin. Subsequent to the survey, the Group reached agreement with the British American Oil Company (Gulf Oil Company), whereby Gulf acquired five permits held by the Group covering high priority anomalies and the airborne survey data. The cost was an undivided 20 percent interest in all lands optioned by Gulf from the Group and in any future lands acquired by Gulf in northern Saskatchewan. In October 1968, as a result of following up airborne anomalies in the Wollaston Lake area, Gulf drilled the first hole into the Rabbit Lake deposit and produced one of the richest intersections found to that time, an impressive 0.5 percent U over 59.4 m.

The Rabbit Lake discovery, together with improving forecasts for uranium demand, precipitated a land staking rush unequalled in Canadian mineral exploration history. During the fiscal year ending March 31, 1969 a total of 31,896,718 acres were acquired under the Mineral Disposition Regulations, 1961. In addition to the 1,543,336 acres acquired through ordinary staking procedures 30,353,382 acres were acquired under 169 prospecting permits. Also, a first for Canadian mineral exploration was the nature of the companies engaged in this rush: most were oil rather than mining companies. Land was acquired as permits covering thousands of square kilometres following the oil industry style. Traditional mining companies, however, moved more slowly, unused to this approach.

At the time Gulf acquired the Dynamic Group permits, Mokta (Canada) Ltd., a subsidiary of Compagnie de Mokta that had been exploring in Canada since 1963 and Saskatchewan since 1964, sent a team to investigate airborne radiometric anomalies in the Carswell Dome area. Initially attracted to the Beaverlodge region, Mokta soon turned their attention towards the Athabasca Basin, undoubtedly prompted by their experience with sandstone hosted uranium deposits in Gabon, West Africa. Investigations in the Cluff Lake area in 1969 resulted in discovery of the D orebody, which was of extremely high grade, and, in the next few years, of the N and Claude deposits.

By late 1972 the exploration rush was over and exploration permits were dropped or reduced to mineral leases and claim blocks. While proving fruitless for many participants, work undertaken at this time provided clues that would lead to other major uranium deposits, notably Midwest Lake.

In 1974, a joint venture group headed by Uranerz Exploration and Mining Ltd. approached the Saskatchewan Government proposing an exploration partnership. The offer was accepted and on June 4, 1974 Saskatchewan Mining Development Corporation (now Cameco Corp.) was born. Exploration by the group produced, in 1975, the Key Lake Gaertner orebody and, in 1976, the Deilmann orebody along strike.

Beginning in 1974, great strides were made by the Saskatchewan Geological Survey, financed under a Canada-Saskatchewan agreement, in geological mapping of the Shield and in interpretation of its evolution. Mapping by G.E. Ray in 1976 and 1977 of the Highrock Lake area revealed the Key Lake deposits as being hosted at the unconformity between graphitic gneisses in the metamorphic basement and the overlying Athabasca Group. It quickly became apparent that a little-known deposit, the Collins Bay A zone, discovered by Gulf in 1971, shared a similar relationship. The role of 'graphitic basement horizons', recognizable as electromagnetic conductors, in controlling the locations of unconformity-type uranium deposits became established as an exploration concept.

This concept led to re-evaluation of the Collins Bay A zone (1976) and discovery of the West Bear deposit (1977) and Collins Bay B zone (1977) by Gulf. Imperial Oil Ltd. (Esso Minerals Canada) and joint venture partners, Numac Oil and Gas Ltd. and Bow Valley Industries Ltd., had cause to review the significance of the Midwest Lake uraniferous boulder train found by prospectors in 1969. The Athabasca boulders comprising the train overlay an indicated basement conductive zone beneath Athabasca sediments estimated to be up to 300 m thick. Drilling in 1977 showed low-grade mineralization at the Athabasca Group/basement unconformity and, in 1978, an economic orebody was delimited.

The Midwest discovery illustrated that deeper parts of the Basin could be successfully explored, in contrast to previous successes which were confined to the margins. Additionally, it led to general acceptance and implementation of the Key Lake exploration model. Thus, by 1978, much of the open ground in the Athabasca Basin was staked and exploration expenditures rose, reaching a peak of around $100 million in 1980.

Several significant discoveries followed within the eastern part of the Basin, for example the Dawn Lake 11 and 14 zones (1978), McClean Lake (1979), Cigar Lake (1981), Jeb (1982), Sue zones (1988) and P2 North (1989). These deposits lack a diagnostic surface expression of mineralization as boulders, and were outlined by systematic drilling of electromagnetic conductors defined by airborne and ground follow-up surveys. Irrespective of these exploration successes the level of activity fell consistently throughout the eighties in response to the massive decline in uranium prices from more than US $40/lb U_3O_8 in 1979 to less than US $10/lb U_3O_8 in 1990.

The uranium production industry was influenced by a number of major events in the seventies and eighties. In October of 1975, Rabbit Lake came on stream reaching planned annual production levels of around 2 million kg U in 1977. Production decreased in 1981 due to depletion of the higher grade portions of the ore zone and the body was mined out by May 1984, although processing continued until October 1985, yielding 15 750 t U (41 million lbs U_3O_8) from 6 million tonnes of ore. The Rabbit Lake operation underwent transition in 1984 and 1985, due to phasing out of the Rabbit Lake open pit, development of the Collins Bay B zone open pit and extensive modification of the mill to accommodate the geochemically more complex ore of the B zone. The Collins Bay B zone achieved first production in November 1985 and was mined out by early 1991, with ore stockpiled for future milling. Mill capacity has been upgraded to around 4.6 million kg U per annum.

Open pit production at Cluff Lake began from the small high grade D zone in the summer of 1980 and mining was completed by 1981, although milling continued until 1984. A second phase of underground and open pit mining and milling of basement hosted lower grade deposits, beginning with the Dominique-Peter and Claude zones, started up in the latter part of 1984. Production is currently somewhat less than 1 million kg U per year. Additional reserves have been identified since 1984 (approximately 5000 t U). The company has also reprocessed Phase 1 tailings, which contained recoverable uranium and 7800 troy ounces of gold.

In 1982, Eldorado shut down its operation at Beaverlodge, bringing to a close all production from the Uranium City area. However, it acquired the assets of Gulf Minerals Canada, Gulf Canada and Uranerz Canada, in effect the ownership of the Rabbit Lake mine/mill complex and the related properties.

The Key Lake Mining Corporation (Cameco Corp.) commenced production, by open pit mining, from the Key Lake orebodies in 1983. The production rate of around 4.6 million kg U annually has made this mine the world's largest uranium producer. The Gaertner open pit was mined out by the end of 1986 and decommissioned. Mining of the larger Deilmann orebody is now in progress.

In 1988 Eldorado and Saskatchewan Mining Development Corporation, owned respectively by the federal and provincial governments, were amalgamated to form Cameco, the world's largest uranium production and marketing company. The corporation presently commands half of the identified uranium reserves of the Athabasca Basin, has majority ownership of production facilities at Key Lake (66 2/3%) and Rabbit Lake (66 2/3%), minority ownership at Cluff Lake (20%), and owns uranium refining and conversion facilities at Blind River and Port Hope in Ontario. Also held are interests in other mineral production and exploration properties.

The Cigar Lake uranium deposit and the Midwest deposit are the subject of test mining projects. The Cigar Lake Mining Corporation was established to manage the development of the giant Cigar Lake deposit with reserves estimated at 150 000 t U. The corporation has sunk a 500 m deep shaft and is developing two levels from the shaft, one above and one below the orebody, to test various mining methods. The operation is scheduled to begin test mining in 1991 and this together with feasibility and environmental impact studies should be completed in 1991 as a basis for a production decision. At the Midwest deposit, operated by Denison Mines Ltd., the underground and test-mining phase was completed in late 1989 and the mine allowed to flood. A 185 m shaft had been sunk and a cross-cut driven above the orebody. Two 1.2 m diameter blind bore holes were drilled from the cross-cut to sample the orebody and test this mining method. Reserves at Midwest are claimed to be 21 500 t U at a grade of 1 percent U and plans for a mine/mill complex with a production capability of 1350 t U per year are being developed.

Industrial Minerals

Industrial minerals and rocks in Saskatchewan have probably been sought after and used in the daily lives and commerce of man since the time of earliest known human habitation, at least 12,000 years ago. Usage of natural mineral materials is recorded by the presence of stone points of the Clovis type in many archaeological

sites throughout Saskatchewan. Remnants of pottery dating back over 2000 years are found mainly south of the Churchill River. Written records of mineral occurrences commence shortly after the arrival of the earliest European explorers: traders and settlers such as Henry Kelsey, La Verendrye, Samuel Hearne, Alexander Mackenzie and the fur traders of Fort Carlton and Cumberland House in the late 18th and early 19th centuries. Sir John Richardson was the first to explore the mineral potential of the province when he arrived in Rupert's Land in 1820 and examined Silurian dolomites at Cumberland House (Kupsch, 1955 p. 8). The territorial rights to Rupert's Land were held by the Hudson's Bay Company until 1870 when they were acquired by the Dominion of Canada. The acquisition laid the foundation for geological investigations in the region by the Geological Survey of Canada, which was established in 1842. Among the earliest geological surveys in the sedimentary basin of the province were those conducted by J. Hector (1859), H.Y. Hind (1858), G.M. Dawson (1875), A.R.C. Selwyn (1880) and R.G. McConnell (1885).

When Saskatchewan attained provincial status in 1905, the Canadian Government retained the rights to its natural resources and the responsibility for conducting geological surveys. Much of the geological work on industrial minerals was conducted by the Canada Mines Branch, formed in 1915. By 1920, the province took a more active role in resource development and established the Saskatchewan Bureau of Labour and Industries. The Bureau initially farmed out much of the exploratory and evaluation work to W.G. Worcester, a ceramic engineer of the University of Saskatchewan. In 1929, the newly formed Department of Geology at the University took on an expanding role in the work. Sedimentary geological investigations were, at that time, conducted by Professor F.H. Edmunds.

In October 1930, by virtue of the Natural Resources Transfer Agreement, all Crown lands, mines, minerals and royalties, except those on Indian Lands, were placed under the control of the province.

A wide variety of industrial minerals occur in the sedimentary basin of Saskatchewan. The more significant occurrences and deposits are shown in Figure 3.

Lignite

The report on the Palliser expedition made by James Hector and Captain Palliser in 1857 is the first record of coal seams in southern Saskatchewan. These investigations were conducted along the Souris Valley near Roche Percée and Estevan on the basis of Indian descriptions of seam outcrops. In 1880, Selwyn conducted the first drilling operations in the Souris area of southeastern Saskatchewan and southwestern Manitoba and encountered several coal seams. The works of Dowling (1914), Rose (1914, 1915, 1916) and MacLean (1917, 1918, 1921) are the earliest detailed studies of coal resources in southern Saskatchewan.

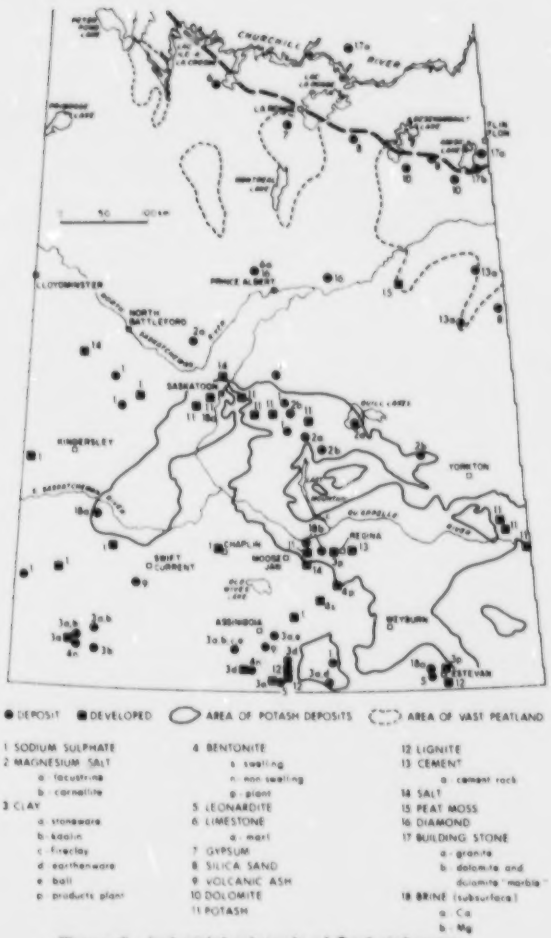


Figure 3 - Industrial minerals of Saskatchewan.

Mining of lignite probably commenced during the early 1870s in the Willow Bunch, Wood Mountain and Cypress areas (Brazier, 1967). This mining was largely conducted by farmers or small groups of farmers using open pit. Where overburden was excessively thick, adits were driven into the hillsides, timbered and the lignite was mined by room and pillar (Rose, 1916). Over 400 mines, operated at various times, are recorded in the files of Saskatchewan Energy and Mines and the Geological Survey of Canada (Irvine *et al.*, 1978). A large proportion of the mines were small, satisfying the demands of single families or small communities.

The first commercial lignite production occurred near Roche Percée in 1880 when Hugh Sutherland, in conjunction with a small group of entrepreneurs, George and Sidney Pocock and Chris Troy, shipped fuel to Winnipeg on barges down the Souris and Assiniboine Rivers. Continuous commercial coal mining commenced in 1890 with the opening of the Hazzard Mine in the Roche Percée area. Although coal mining in the region west of the Souris area (Willow Bunch to Cypress) was active until about 1954, production from the Souris coalfields has always dominated the industry.

Lignite gained an increased status in the provincial economy between the early twenties and late forties with its use as an industrial fuel in Regina, Moose Jaw, Brandon, Winnipeg and, to a lesser degree, Swift Current, Saskatoon and some western Ontario communities. Eastern markets were enhanced by an American ban on coal exports during World War I. Later, during the depression, the incentive to use western coals was provided by subsidies granted to railroad companies (Broughton, 1978).

A fuel shortage during World War I inspired the Federal and Saskatchewan governments to establish a Lignite Utilization Board to investigate methods of upgrading lignite to a more versatile fuel. Briquetting was the favoured option and in 1921 a plant was established. It operated unsuccessfully until 1923 when it was closed. The plant was sold to Western Dominion Collieries Ltd. in 1927 and was modified considerably. Later it was resold and in 1931 began a successful operation.

With the exception of small local pit operations in favourable areas, lignite mining was largely conducted underground. The Sunlight Coal Co. was the first to attempt open pit mining on a large scale in 1927. The experiment and the company failed due to problems with wet lignite freezing in the rail cars. In 1930, the Truax-Traer Coal Co. commenced a successful large-scale stripping operation which heralded the gradual demise of conventional underground mining. The considerable decline in mining costs broadened the market area to include large industrial users as far east as the Lakehead.

By 1955, underground operations were relegated to history. Mines in the Cypress and Willow Bunch areas could not compete with the more efficient mines of the Souris area and their commercial production ended in 1954 and 1955 respectively. Lignite mining was then concentrated within a group of four large companies: Western Dominion Coal Mines Ltd. (60%), Manitoba and Saskatchewan Coal Co. (21%), Roche Percée Coal Mining Co. (10%) and Eastern Collieries (9%).

From 1940 to 1958, growth in lignite exports outpaced growth of in-province usage which had remained fairly stable. The year 1959 marks the beginning of a rapid increase in provincial utilization when the first unit of the Saskatchewan Power Corporation Boundary Dam thermoelectric generating plant at Estevan started up. This was followed, in 1960, by the second unit, and by the third, fourth and fifth units in 1969, 1973 and 1977, thereby accounting for a tripling of in-province consumption of lignite. Production from the Utility Mine, operated by Manalta Coal Ltd., is dedicated to this plant. The growth of exports in the period increased significantly through sales to Manitoba and Ontario. Figure 4 depicts lignite production and in-province utilization since the earliest years of mining. The latest rise in lignite production and provincial usage may be attributed to commencement of operations by the first 600 MW power unit of the Coronach Power Plant in 1980 and by the second unit in 1982. The plant is supplied by the Poplar River Mine, near Coronach in the Willow Bunch coalfield. The mine is to be replaced by Prairie Coal Ltd. Willow Bunch Mine a few miles north.

A widespread exploration program for uranium in the Tertiary lignites was conducted by industry in the late sixties. Although prospects for economic uranium deposits proved poor, the extensive shallow drilling revealed the

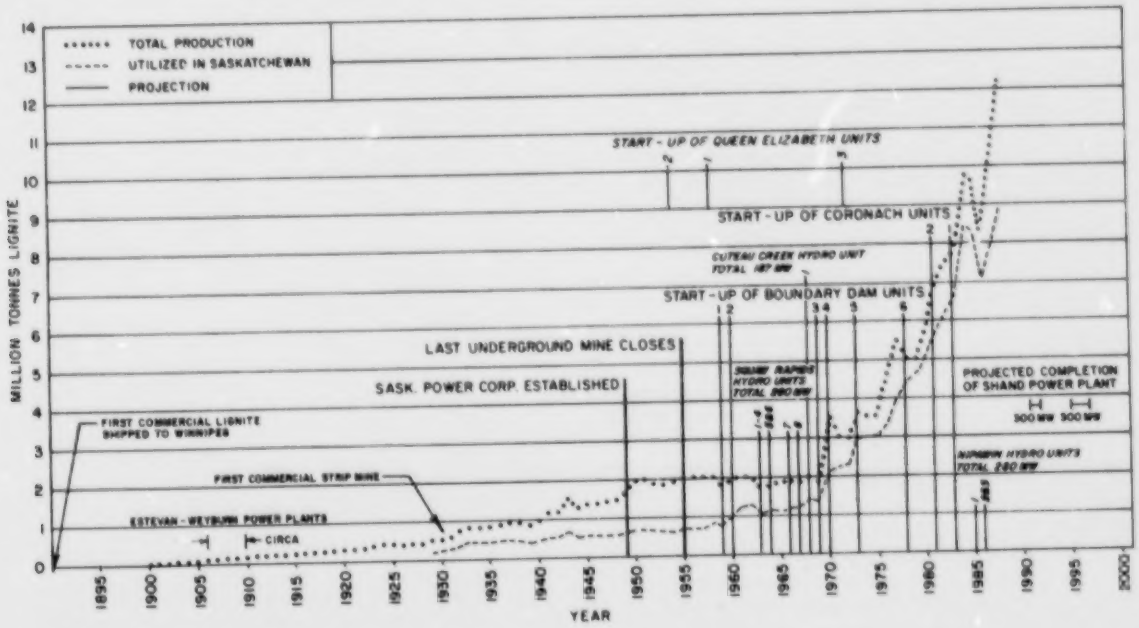

TOTAL PRODUCTION
UTILIZED IN SASKATCHEWAN
PROJECTION
START - UP OF QUEEN ELIZABETH UNITS
START - UP OF CORONACH UNITS
START - UP OF BOUNDARY DAM UNITS
LAST UNDERGROUND MINE CLOSES
SASK. POWER CORP. ESTABLISHED
FIRST COMMERCIAL LIGNITE SHIPPED TO WINNIPEG
FIRST COMMERCIAL STRIP MINE
ESTEVAN - BOUNDARY DAM POWER PLANTS
PROJECTED COMPLETION OF SHAND POWER PLANT
MILLION TONNES LIGNITE
YEAR

Figure 4 - History of lignite production and utilization in Saskatchewan

potential for extensive coalfields in the Willow Bunch, Wood Mountain and Cypress-Shaunavon areas. In 1972, a coal evaluation program was commenced under a Federal-Provincial agreement by the Geological Survey of Canada, Saskatchewan Mineral Resources and the Saskatchewan Research Council. The resulting report, including an atlas and an open file microfiche catalog of the stratigraphy in about 1200 boreholes, is the major reference on lignite resources in Saskatchewan. A major effort is under way to improve the resource definition and determine mineable reserves. A substantial increase in the size of the data base since the 1972 evaluation program has made this possible. The project is a cooperative effort between the Geological Survey of Canada (GSC) and Saskatchewan Energy and Mines. Computer modelling techniques developed by the GSC are being employed.

Clay

Cretaceous and Tertiary strata (Plate 1) in southern Saskatchewan and, to a lesser degree, Quaternary deposits are host to a wide variety of clays of potentially great economic significance. The low bulk value of clay materials demands surface or near-surface occurrence and access to substantial markets. Clays of the Upper Cretaceous Bearpaw and Whitemud Formations and the Tertiary Ravenscrag Formation satisfy local demand throughout the southernmost region of the province. However, their remoteness from major market areas historically has hindered the industry from reaching its full potential.

Marine clays and shales of the Bearpaw Snakebite Member are well exposed along the Blackfoot ridge in the Truax-Avonlea area. Here, up to four beds of swelling bentonite occur in thicknesses ranging from 30 to 76 cm at or near surface.

The Upper Cretaceous Whitemud Formation is a sequence of terrigenous kaolinitic sands, clays and sandy clays cropping out as extensive erosional remnants from the Cypress area in the west to the Big Muddy River system in the east. Smaller outliers are present near Halbrite, Claybank and the Vermillion Hills. The important deposits are those in the Eastend - Shaunavon, Wood Mountain - Willow Bunch and Claybank districts. All are of kaolinite but vary widely in physical and chemical properties and consequently in prefiring and firing characteristics and ultimate application.

Clays of the Tertiary Ravenscrag Willow Bunch Member are kaolinite and smectite . The kaolinite-based clays occur high in the formation and are exposed or lie near the surface in the dissected upland region south of the Big Muddy system, especially south of Big Muddy Lake, west and north of Big Beaver, southwest of Harptree, and south and west of Willow Bunch, Rockglen, Strathallen and the uplands southeast of Wood Mountain. The clays are suitable for earthenware and stoneware, firing to maturity at lower average temperatures than Whitemud clays, in part because of a higher alkali content.

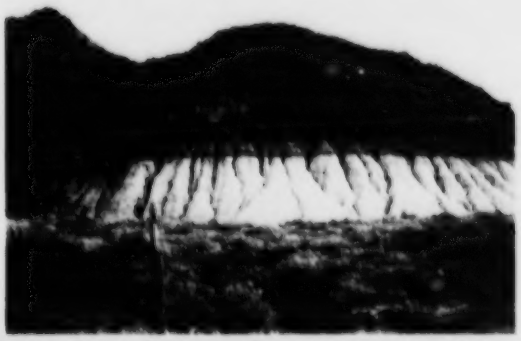


Plate 1 - Tertiary Ravenscrag Formation overlying Cretaceous Whitemud Formation, Big Muddy Valley. Contact is near the base of the thickest dark lignitic zone.

Bentonites of the Ravenscrag Formation are concentrated largely between the eastern end of Twelvemile Lake and St. Victor. A deposit of nonswelling bentonite near Rockglen, once thought to be of Paleocene (Ravenscrag) age is probably Eocene-Oligocene.

The economic and industrial significance of Saskatchewan clay resources have been long recognized, as early, in fact, as the work of McConnell (1885) and Dawson (1875). However, the first major studies were conducted by Ries and Keele (1913), Rose (1916) and Davis (1918). Among many other clay-related investigations in the province, the work of McLearn (1928, 1930) and Worcester (1950) are outstanding. Although Worcester had published numerous clay-related papers, he synthesized 20 years of investigations from 1927 to 1947 in his 1950 report which remains an outstanding reference.

The earliest recorded clay production from the region including Alberta and Saskatchewan was in 1886. Records of continuous production for Saskatchewan alone date from 1905. With a few exceptions, the clay industry during the early decades of the 20th century consisted of numerous small plants largely producing common brick for the local market. Most utilized local glaciolacustrine clays. Some of the larger plants, such as the Saskatchewan Clay Products Co. (later the Dominion Fire Brick and Clay Products Co.) at Claybank, the Estevan Coal and Brick Co. and the Bruno Clay Works Ltd., had diversified to include face brick, drain tile, structural tile or fire brick.

The Claybank plant commenced operation in 1911, utilized Whitemud clays and was the only plant to produce refractories in the Province. The plant was taken over by A.P. Green (Canada) Ltd. in about 1955 and operated until 1989 when it closed down.

The Estevan Coal and Brick Co. (probably the former Eureka Coal and Brick Co.) commenced operations in about 1913 and was taken over in 1925 by International Clay Products Ltd. The company produced common and face brick by the dry press and stiff mud technique and in 1925 developed a stiff-mud textured face brick.

In 1944 the plant was purchased by the Crown and became the Clay Products Division of Saskatchewan Minerals Corporation. Later, as it is at present, the company became Estevan Brick Ltd., although ownership has changed twice since then, the current owner being Thunderbrick Ltd.

The Whitemud ball clay has been mostly exported. This high quality light-burning clay was mined since the mid-twenties. Early production came from surface workings at the Midland mine near Willow Bunch between 1925 and 1932. Later, as easily available material was depleted, an adit was driven into the hillside and underground mining continued until 1941 when the operation closed. Stoneware clays and ball clays from the Willows-Readlyn area found a market in whiteware potteries in Ohio and also, for many years, with Medalta Pottery in Medicine Hat who played a significant role in supplying the armed forces with tableware during World War II. The high plasticity of the ball clays demands blending with less plastic clays to minimize dry shrinkage. To this end, Whitemud stoneware clays of the Eastend and Willows area were used. These stoneware clays had also found a market in structural ware and sewer pipe production in Medicine Hat by Medicine Hat Brick and Tile Co., in the Regina plant of Western Clay Products Ltd. (now under IXL Industries Ltd.) and in facebrick production at Estevan.

Utilization of the Whitemud sandy kaolinized basal beds has thus far been limited to blending with plastic clays to increase refractoriness and reduce dry shrinkage in brick production. The high kaolinite content of the Whitemud, ranging from about 45 percent to over 60 percent in the Wood Mountain area, has attracted a considerable amount of attention in the last 40 years. Studies have been directed at resource definition, mineralogical characterization, sand-clay separation, technology, stratigraphy, alumina content for potential aluminum production, refractory materials and kaolin filler. Of note are the investigations by the federal Department of Mines and Resources (1948), Carlson and Babey (1955), Spyker *et al.* (1954), Brady (1962) and unpublished work of the Saskatchewan Research Council.

Hudson (1967) reported that the Wood Mountain kaolin is about 50 percent less than 2 microns in size and has a reflectance value of about 70. Standard bleaching tests had failed to improve the whiteness. It was deduced, from laboratory examination, that the colouration was likely due to iron in solid solution with kaolin. More recent investigations by the Saskatchewan Research Council have identified smectite and extremely fine ilmenite as the main agents of colouration. Differential flocculation and high intensity wet magnetic separation combined with chemical bleaching have succeeded in raising the reflectance to values in excess of 80. The work represents a significant milestone in Whitemud kaolin investigations, in that it helps to dispel misconceptions of its potential value in the filler industry.

Since 1984, Ekaton Industries Inc. has conducted exploration and evaluation of kaolin resources in the Eastend and Wood Mountain areas, and proposed to develop the Wood Mountain area. The company excavated several thousand tonnes of kaolinized sand for processing at a pilot plant near Regina. Success was reported in upgrading the kaolin to paper filler standards. Calcining tests were also reported as successful.

Bentonite was recognized as a potentially valuable industrial clay as early as the work by Spence (1924) who reported and described occurrences in the Pasquia Hills, in southwestern Saskatchewan near Eastend and near St. Victor. Worcester (1937, 1938) conducted the first serious work on these deposits. Discovery of major oil reserves in western Canada in the forties and fifties heightened interest in the bentonite. Much of the research of this resource was conducted during 1950 by Tomkins (1952) and Tomkins *et al.* (1954).

Exploration and evaluation of bentonite by industry commenced in earnest during the early seventies when Contrex Ltd., Flin Flon Mines Ltd. and Inland Cement Industries Ltd. engaged in field and laboratory work on the Bearpaw bentonites in the Truax area.

The investigations, in which Inland Cement Industries Ltd. and the Saskatchewan Research Council played an important part, culminated with the establishment by Avonlea Mineral Industries Ltd. of a bentonite quarry near Truax and a processing plant at Wilcox in 1978.

Quaternary glaciolacustrine clays were utilized by many small brickyards across Saskatchewan, at least since 1908 when the Bruno Clay Works Ltd. commenced operation. Worcester (1950) recorded 26 individual brickworks that had operated at one time or another in widely scattered areas of the province up to 1950. Many fell victim to small local markets and to lack of working capital and technical and business skill.

A considerable amount of research was conducted on Quaternary clays during the fifties for their bloating characteristics and their use as light-weight aggregates in concrete, especially by the federal Department of Mines and Technical Surveys and by Sacuta (1956). Two plants presently produce light-weight aggregate from local clays, one in Regina and the other in Saskatoon. These clays are also used as a source of aluminosilicate for cement production by Inland Cement Industries Ltd. in Regina, the sole cement producer in Saskatchewan.

Potash

Middle Devonian potash occurs near the top of a thick sequence of halite and anhydrite comprising the Prairie Formation. In Saskatchewan, this formation ranges from 400 to 2740 m in depth and attains a maximum thickness of about 213 m.

Four distinct potash-bearing members are recognized (Figure 5). These are, in ascending order, the Esterhazy, White Bear, Belle Plaine and Patience Lake, and range in thickness up to nearly 30 m (Fuzesy, 1982). The sylvinite ore consists of a mixture of halite (NaCl), sylvite (KCl), carnallite (KCl. $MgCl_2$. $6H_2O$) and insolubles. It averages between 21 and 27 percent K_2O, reaching 30 percent in some areas (Fuzesy, 1982).

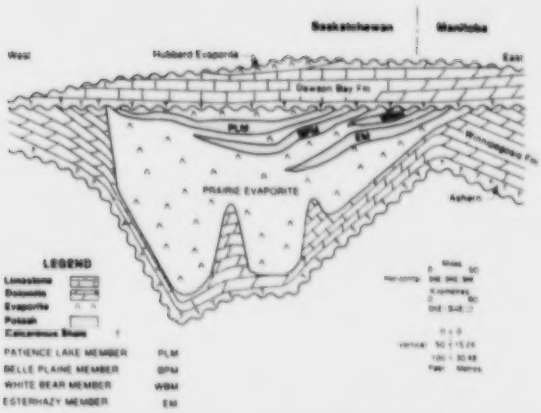


Figure 5 - Diagrammatic cross-section through the Prairie Formation in Saskatchewan and Manitoba (after Fuzesy, 1982).

Potash in south-central Saskatchewan was discovered in 1942 near the town of Radville at a depth of 2332 m as a result of petroleum exploration. This was followed in the same year by a similar discovery near Ogema. It was not until about 10 years later that a well was drilled specifically for potash evaluation.

The first attempt at commercial potash mining in Saskatchewan was that of the Western Potash Corporation Ltd. in 1951. After failing at solution mining near Unity, the company commenced the excavation of a mining shaft in 1952. Difficulties with water inflow followed and the shaft was abandoned and sealed in 1968.

Potash mining was initiated by the Potash Company of America in 1958. With the exception of an interruption between 1959 and 1965 due to brine inflow, the mine was essentially in continuous production until 1987 when brine inflow from older workings suspended production. Between 1962 and 1970, about 40 companies were involved in potash exploration. Nine successful ventures in addition to the Potash Company of America resulted from these efforts.

Salt

Salt (sodium chloride) occurrences in Saskatchewan are of three types: 1) saline springs, 2) subsurface formation brines, and 3) extensive strata of massive halite.

Saline springs are common to the region flanking the north slope of the Pasquia Hills in east-central Saskatchewan, near the limit of Devonian rocks (Simpson and Dennison, 1975). A few other saline springs occur in scattered localities in western Saskatchewan and along the northern limit of the Athabasca Basin.

Generally, the salinity of Phanerozoic brines increases southward and southwestward toward the Williston Basin centre. Maximum chloride contents in excess of 189 000 mg/l are recorded in the deeper clastic aquifers and about 38 000 mg/l in the shallower and younger aquifers of the Mesozoic (Simpson and Dennison, 1975). Massive halite and mixed halite-sylvite-carnallite deposits of the Middle Devonian Prairie Formation represent by far the largest salt resource in the province.

The salt requirements of the early plains settlers and traders from about 1800 to 1876 were satisfied by salt springs west of Lake Winnipegosis and Lake Manitoba. Men freed from Hudson's Bay Company service and employees of the Northwest Company evaporated the brines in iron kettles and troughs and supplied the salt to the Hudson's Bay Company posts from Norway House to Fort Qu'Appelle and to the Red River Settlement (De Lury and Cole, 1928). With the arrival of the railway in 1882, Ontario became the main supplier of salt to the west.

The earliest known production of salt in Saskatchewan was by the Senlac Salt Co. in about 1920 at Salt Lake south of Senlac in the west-central area. A small solar evaporating system was replaced after a short time by three large open evaporating pans heated by coal fires. The operation closed down after two or three years.

In 1932, while drilling for oil in the Simpson area, the Simpson Oil and Gas Co. encountered salt brine at a depth of 1067 m (Worcester, 1935). The brine was likely associated with the Upper Devonian Souris River Formation where massive halite deposits of the Davidson Member are present. The company established a small evaporating plant with a capacity of several tonnes of salt per day. Production ceased in 1935.

In 1946, salt and potash of the Prairie Formation were encountered in the Verbata No. 2 well near Unity in west-central Saskatchewan. By May 1949, the Prairie Salt Co. had developed a salt brining operation there and made its first shipment of product. The plant is now operated by the Sifto Salt Division of Domtar Inc.

The International Minerals and Chemical Corporation (Canada) Limited, engaged in potash production since 1961, also produces byproduct salt for road ice control. Other salt producers include the Saskatoon Chemicals Co. (Division of Weyerhaeuser), which commenced a brining operation from the Prairie Formation near Saskatoon in 1968 for caustic soda and chlorine production, and the Canadian Salt Co. Ltd., utilizing byproduct salt since 1969 from the nearby Kalium Chemicals solution potash mine for various products.

Sodium Sulphate

Natural sodium sulphate deposits occur in numerous alkaline lakes with restricted drainage in southern Saskatchewan (Tomkins, 1954; Last and Schweyen, 1983). The sodium sulphate lake brines are primarily of the Na-Mg-SO_4 type, giving rise to the minerals mirabilite ($Na_2SO_4.10H_2O$) and, to a lesser extent, thenardite (Na_2SO_4), bloedite ($Na_2.Mg(SO_4)2.H_2O$) and epsomite ($MgSO_47H_2O$). The solutes enter the lakes through the leaching effects of surface and near-surface water in the surrounding terrain and via inflowing brackish and brine springs. Evaporative concentration of the brines takes place during the warm, dry summers. If the salt con-

centration is sufficiently high, as it is in many alkaline lakes, crystallization follows with declining ambient temperatures in the autumn.

Some alkaline lakes, such as the Quill Lakes, remain as brine and others produce a seasonal crystal bed. The crystal bed may be partially or wholly dissolved during the following season. Partial seasonal dissolution results in the accumulation of permanent crystal beds, some of which are of exceptionally high grade, containing in excess of 90 percent salts of sodium and magnesium. Permanent crystal beds are typically 1 to 5 m thick but may, in some lakes, reach far greater thicknesses; (e.g. more than 30 m in Ingebright Lake near Fox Valley of southwestern Saskatchewan). The principal impurities in salt beds are clay, silt, sand and organic matter including algal and various high-salinity aquatic fauna.

In Saskatchewan there are 21 major natural sodium sulphate deposits with more than 500 000 tonnes of reserves each. Eleven others are 100 000 to 500 000 tonnes in size and thirteen are less than 100 000 tonnes (Tomkins, 1954). At least 25 others are known but have not been investigated in detail (Cole, 1926). The total resource of anhydrous sodium sulphate contained in the 21 largest deposits is about 50 million tonnes.

Discovery of sodium and magnesium sulphate salts resulted from a search for potash in the alkali lakes. Because of the potash shortage during World War I, many of these lakes were claim staked in 1918. Most of the claim holders allowed their claims to lapse when no potash was found. A few had discovered substantial deposits of Epsom and Glauber's salts.

The earliest attempt at alkali recovery was made by the Canadian Salt and Potash Co. of Canada Ltd. in 1918-19 at Muskiki Lake. Shortly thereafter, from 1921 to 1924, the Canada Department of Mines embarked on extensive surveys of the alkali lakes and their deposits. This work (Cole, 1926), was instrumental in the development of the resource. Tomkins (1954) added significantly to the description of the major deposits and to understanding of the technology of production. Recent research by Last (1983), Last and Schweyen (1983) and Slezak and Last (1984) examined the geology, sedimentology and geochemistry of the saline lakes of the plains region. Although little has been published on the research and experimentation by the industry into the mining, processing and purification of sodium sulphate, the success of the operations attests to their important contribution.

Since the first attempt at sodium sulphate mining, more than twenty companies have been involved in development work over the past 70 years. Four are operating today.

Silica Sand

Silica sand in Saskatchewan is largely restricted to the Lower Cretaceous Mannville and the Ordovician Winnipeg Formations. Scattered occurrences of glacial or recent lacustrine outwash or beach sands of somewhat lower quality are also known.

Cretaceous silica sand resources are the most widespread and best known in the province. The major deposits are located along the Red Deer River about 48 km northeast of Hudson Bay and over an extensive region south of Wapawekka Lake and Lac La Ronge. Babey (1955) reported a silica content of 97.4 to 98.5 percent in untreated Red Deer River sands. Washed and tabled product ranged from 99.0 to 99.6 percent silica. Sieve analyses indicated 77.4 to 86.9 percent in the -20 to +65 mesh range. Babey (1955) and Collings and Andrews (1986) agree on the potential value of the sands for glass and as foundry material.

The Red Deer River silica sands were discovered by the Howryschuk brothers in about 1941. Worcester (1943) conducted the first examination of the deposit in 1942, followed by Wickenden in 1945. The federal Department of Mines and Technical Surveys performed beneficiation and evaluation work on the sands periodically between 1946 and 1986. Babey (1955) and Beck (1974) carried out investigations for the province. Since their discovery, the Red Deer River deposits have gone through several cycles of dispositions by industry but little or no work had been conducted until Prairie Silica Ltd., King Resources Ltd. and Northland Distribution and Supply Co. took an interest between 1973 and 1983. In 1986, Red Deer Silica Inc. announced plans to quarry the deposit with proven reserves of 14 million tons (12.7 million tonnes) and to establish a processing plant at Hudson Bay.

Lower Cretaceous silica sands in the Wapawekka Lake and Bow River areas (Plate 2) were examined by Pearson (1961) and Hudson (1961), respectively. Langford (1973) recognized their economic potential for silica and associated kaolinite, and indicated the immensity of the resource. Recent analyses of controlled samples taken by Saskatchewan Energy and Mines are presented in Table 1.

Other silica sand sources include scattered outcrops of Ordovician Winnipeg Formation sand in the Hanson-Deschambault Lakes area.

Among the earliest works on the Winnipeg Formation were those of Kupsch (1952) and Byers (1957). Later, Paterson (1971) studied the formation on a regional stratigraphic basis. Holocene Resources Ltd. conducted an evaluation of the Winnipeg sand for its potential as a hydraulic fracturing sand and a source of industrial silica.

No major development has been undertaken to date, except for production of sand for silica flux by Hudson Bay Mining and Smelting Co. Ltd. since 1933. An estimated 6.35 million tons were used for this purpose by the copper smelter. The Red River deposit is under development by Red Deer Silica Inc.

Plate 2 - Lower Cretaceous silica sand outcrop, Nipekamew River.

Table 1 - Average Size Distribution and Sand Analyses from the Nipekamew River Site

Mesh Size	*Av.%*	*Av.SiO_2%*	*Av.Kaolin%*
Upper Unit (13 m)			
-5+10	9.7	98.62	1.25
-10+18	14.4	98.74	1.15
-18+35	25.4	98.35	1.55
-35+60*	19.3	97.33	2.50
-60+100	10.2	95.60	5.70
Lower Unit (4 m)			
-60+100	32.7	99.56	0.53
-100+200	41.8	98.31	1.58
-200	11.5	62.29	39.10

*Trommeling and washing of one sample from the -35+60 mesh fraction increased the silica content from 98.34 percent to 99.03 percent.

Sand and Gravel

Sand and gravel deposits are, for the most part, intimately related to the history of glaciation, deglaciation and postglacial geomorphic processes throughout Saskatchewan. Proglacial deposits, including outwash plain, deltaic, valley train and meltwater stream, and postglacial alluvial terrace and channel deposits tend to be very large and infrequently very coarse (Mollard and Mollard, 1987). Smaller deposits are associated with kames, kame deltas, kame terraces, eskers and crevasse fillings. Ice-contact deposits are usually small, more abundant and more variable and complex. Of local significance, specifically in south-central and southwestern Saskatchewan, are the coarse Tertiary quartzite gravels of the Eocene-Oligocene Swift Current and Cypress Hills Formations and the Miocene Wood Mountain Formation. Reworked equivalents of these provide material for direct use or as crushed rock.

Mollard and Mollard (1987) indicate, on the basis of about 10,000 gravel prospects mapped from airphotos in the past 40 years, that there is about one small sand and gravel prospect for every 26 km^2 and about one large prospect for every 2600 km^2 investigated. Most of the larger deposits range from 2.5 million to 12.7 million tonnes. The largest contains about one billion tonnes.

The relative abundance, ease of discovery and widespread occurrence of sand and gravel deposits throughout much of Saskatchewan have resulted in a paucity of published information on the resource. The earliest are probably those of the Geological Survey of Canada from 1916 to 1920. Some of the most significant with respect to sand and gravel resource location are those of the Saskatchewan Research Council, particularly by E.A. Christiansen between 1956 and 1970 on glacial and surficial geology, groundwater, preglacial valleys and Pleistocene stratigraphy. Geotechnical engineering and geological consulting firms, rural municipalities, private contractors and the provincial highway construction authorities have made considerable contributions to sand and gravel resource location, development and supply. However, little of the data is available for publication. The depletion of many of the small deposits, particularly in proximity to some urban areas, is a concern of growing significance. The rising cost of transportation from more distant deposits has aggravated this problem for many communities. The Saskatchewan Research Council has responded by embarking on a long-term aggregate resource evaluation program. Maps being published under the program are 1:250 000 scale surficial geology and aggregate resource potential maps and 1:50 000 scale aggregate resource maps for areas around urban centres.

Peat

The major peatlands of Saskatchewan cover about 4 million ha in a 200 km wide belt extending south from the Precambrian Shield edge and from the Manitoba to the Alberta borders (Scott, Korpijaakko and Tibbetts, 1980). The region consists of extensive uplands with relatively sparsely scattered peatlands and intervening lowlands with widespread peatlands (Guliov, 1981).

Prior to 1978, peat resource investigations were cursory at best and localized, except for the deposit about 30 km east of Carrot River which is the southward limb of a vast peatland extending north and northeastward. This deposit is the only producing bog in the province. Although sporadic investigations and small-scale production had probably taken place prior to 1945, the first

serious examinations of the resource appear to have been conducted by Hastings (1945) and Leverin (1946).

Troyer (1985) conducted the first regional investigation of peat resources in Saskatchewan with funds provided by the Canada-Saskatchewan Interim Subsidiary Agreement on Mineral Exploration, supplemented by independent provincial funding. He found that peatlands in the region west of the La Ronge - Montreal Lake region contain a large proportion of well-humified sedge fuel peat generally with a sphagnum cover; that the sphagnum moss layer appears to be best developed in the La Ronge area; and that, although moss peat resources are substantial, the fuel peat potential is greater. The region to the east was not examined.

Commercial peat moss production was initiated by the Carrot River Peat Moss Co. Ltd. in 1959. After a period of bog preparation and drainage, production of block-cut peat commenced. Blocks were arranged on the bog surface for drying and then transported to a plant near Carrot River where they were hammer-milled and bagged. In 1966, Asphalt Services Ltd. became a partner and the first shipment of floral peat was made to the tree nursery at Indian Head, Saskatchewan. Production was converted to a milling and vacuum operation in the late 1960s and market growth ensued during the 1970s. In 1980 the company was sold to the crown corporation, Saskatchewan Minerals, Peat Moss Division. In 1988 the operation was sold to Premiere Sask. Inc.

Prior to 1986, production had risen to about 300,000 bales of 0.1 m^3 in volume of peat compressed 2.5:1. In 1986 production rose to about 700,000 bales (about 27 kg/bale).

Diamonds

Documented diamond exploration in Saskatchewan dates from 1948 when John G. Johnson, a prospector from Flin Flon, claimed to have found five diamonds. The find was never officially corroborated. No further finds were reported by Mr. Johnson despite his permission to acquire a license to explore an area of one hundred square miles in a region now known to contain kimberlite bodies.

A second flurry of diamond exploration occurred from 1961 to 1963. In June 1961 Mr. Max Pellack filed thirty claims in the Prince Albert area and claimed to have found two diamonds about one quarter inch in diameter. The ensuing staking rush resulted in about five hundred claims being filed in the area. The find could not be substantiated and no further reports of diamond finds resulted from this rush.

In November 1988 an official announcement was made of the discovery of a kimberlitic body in the Sturgeon Lake area, about 30 km northwest of Prince Albert. The discovery was made somewhat earlier, probably by Mr. Jacque Letendre of Monopros Limited, a subsidiary of De Beers. The kimberlite was reported to be diamondiferous but uneconomic. Although considerable staking took place a few months prior to the announcement, it accelerated rapidly after the news release so that by the end of 1988 nearly 332 000 hectares had been staked. The areas covered were largely from Prince Albert to as far north as Prince Albert National Park and eastward to the Choiceland area.

By May 1989 Claude Resources had announced the discovery of a kimberlite occurrence about 2 km northwest of the Sturgeon Lake discovery. In September of 1989 Uranerz Exploration and Mining Limited and Cameco announced the discovery of seven kimberlite pipes in the Fort a la Corne area east of Prince Albert. Microdiamonds were found in one of them. Two macrodiamonds were reported by Uranerz in November of 1990; one of 2 mm size of industrial quality and one of 4 mm size of undisclosed quality. Four more macrodiamonds have been added to this total in early 1991. Two gem-quality stones weigh 0.49 and 0.14 carats.

Since the initial discoveries diamond exploration has spread southward and southwestward nearly to the U.S. border and northward onto the Precambrian Shield. Much of the province appears to be favourable ground for diamond prospecting. The early and continued exploration successes are likely to ensure a high level of interest in the province in the foreseeable future.

Petroleum and Natural Gas

Records of drilling in Saskatchewan indicate that the first well drilled was by the Geological Survey of Canada at Fort Pelly in 1874-75 and the second at Fort Carleton in 1875. Depths reached were 153 and 53 m respectively. Around 1883, several "borings" were conducted by the Canadian Pacific Railway at Grenfell, McLean and Belle Plaine. These wells were for the purpose of obtaining water, but one account of the well at Belle Plaine, which reached 473 m, records a "small gas flow". This then could be the first indication of hydrocarbons in Saskatchewan.

From 1900 to 1919 there were 14 wells drilled and from 1920 to 1929 there were 18. All were unsuccessful. However, success did come with the discovery of commercial natural gas in the Lloydminster area of western Saskatchewan. The Lloydminster Gas Company No. 1 well was spudded on November 22, 1933 and encountered gas on January 9, 1934. This led to the establishment of the Lloydminster gas field with reserves of 231.3 x 10^6 m^3, of which some 7.3 X 10^6 m^3, remain after 55 years of production. The gas is from the Colony Sand of the Mannville Formation (Cretaceous) at 518 m depth.

Altogether, 103 wells were drilled from 1930 to 1939, including several in the Pasquia Hills region of eastern Saskatchewan. There were 11 successful gas wells. Although oil was found in the Lloydminster area in 1935, it was not in commercial quantity.

Exploration and development grew substantially from 1940 to 1949, with 413 wells being drilled (109 in 1947 alone). Two new gas pools were established in the Unity area of western Saskatchewan, in the Mannville Unity Sand at 632 m in 1944 and the Viking Sand

(Cretaceous) at 503 m in 1945. The former is now depleted after producing some 267 x 10^6 m^3 of gas.

For the first time commercial oil was also found. Heavy (low-gravity) crude had been discovered in nearby Alberta in 1943. The discovery well was Sparky No. 1, 6 km west of Lloydminster, producing from the Mannville Sparky Sand. In 1944, the Silverdale well, 8 km south of the city, located commercial oil in Saskatchewan in the same strata and, by the end of the decade, four oil fields had been established. These were Lone Rock, Dulwich and Marsden, all producing from the Sparky Sand, and Gully Lake which produced from another Mannville sand, the Waseca. All four fields are still producing. Shallow gas was found in the mid-forties in the Kamsack area of eastern Saskatchewan, but was noncommercial.

The number of wells drilled from 1950 to 1959 was 7114, reflecting the tremendous increase in activity over the years. (It should be noted here that some of those wells were put down by the burgeoning potash industry, whose wells are also included in future totals). The year 1957 alone accounted for 1258 wells. This was paralleled by discoveries of oil and gas which created some 119 new fields. Nine of these were in the Lloydminster area, heavy oil reservoirs similar to those already found. But most exciting for the province was the discovery of new types of oil and gas in new areas and at new stratigraphic levels.

First was the discovery in 1951 of the Coleville field in the Kindersley area of western Saskatchewan. This field produced heavy crude from the Bakken Sand (Mississippian) at 823 m depth. With initial reserves of 10.469 x 10^6 m^3 of oil, it is still producing and has remaining reserves of some 3.169 X 10^6 m^3. Five other similar fields were discovered during the period, some of which are in Mannville (Cretaceous) strata.

Also in 1951, the Coleville-Smiley and Brock gas fields were discovered in the same area. Those produced from the Viking Sand (Cretaceous) at approximately 700 m and were the forerunners of nine similar fields found before 1960.

In 1952, three new areas opened up. The Wapella field was discovered in southeastern Saskatchewan. Medium crude was produced from the Wapella Sand (Jurassic/Cretaceous) at a depth of 701 m. It has produced 1.605 X 10^6 m^3 and still has reserves of 0.915 X 10^6 m^3. In spite of exploration, it remained the only field of its type in the area until two others were discovered in 1984. In southwestern Saskatchewan, medium crude found in the Fosterton area in the Roseray Sand (Jurassic) at 975 m preceded seven similar fields that same year, including reservoirs in the Shaunavon (Jurassic) and Success (Mannville) Formations. A total of thirty-one fields were in existence by the end of 1959. The Burstall natural gas field was established in 1952 adjacent to the Alberta border in southwestern Saskatchewan. It produced gas from the Medicine Hat Sand and Milk River Formation (Cretaceous) and was joined by the Hatton field in 1953. The latter has reserves of 31 025.0 X 10^6 m^3 of gas. In 1953, light crude oil was discovered in the Kindersley area of western Saskatchewan. The Whiteside and Smiley-Dewar fields began production from the Viking Sand (Cretaceous) and were joined by another four fields by the end of 1959. These included Dodsland which still has reserves of approximately 3.587 X 10^6 m^3.

Major discoveries of oil in the Mississippian of southeastern Saskatchewan occurred in 1953 when medium crude was produced at the Midale field from the Midale and Frobisher Formations at approximately 1400 m and in the Freestone field from the Frobisher-Alida Formation. The Midale field alone has produced 18.391 X 10^6 m^3 of oil. By the end of 1959 there were 19 such fields. Light crude entered the market in 1954 from four different fields, notably the Steelman, from Midale and Frobisher strata at about 1400 m depth. This field has produced some 38.9 X 10^6 m^3 of oil and has some 5 X 10^6 m^3 of reserves. Thirty-six fields were producing Mississippian light crude by 1960.

Wells drilled in Saskatchewan continued to increase in number during the sixties. Some 10,069 wells were recorded, peaking at 1458 in 1965; thereby creating 103 new fields, mostly in the areas already under development. In the Mississippian of southeastern Saskatchewan, there were 35 fields of light crude and 20 fields of medium crude; in the Cretaceous of the Lloydminster heavy crude area, 24 new fields; and in the Jurassic/Cretaceous of southwestern Saskatchewan, 15 new fields of medium crude.

The discovery of Ordovician oil in the Red River Formation in 1963 was of particular interest and importance during this period. This took place at 3063 m in the Lake Alma district of southeastern Saskatchewan, and was followed by a similar discovery at nearby Beaubier in 1967.

In the Hummingbird area some 16 km to the west, Devonian oil was found at 2326 m in the Birdbear Formation in 1966, and in the Kisbey area (some 113 km to the east) in 1968. Also in 1968, a good showing of Birdbear oil was noted in the Smiley area, near Kindersley of west-central Saskatchewan.

On the other hand, a major exploration effort, called the Pheasant Winnipegosis Project, drilled 48 wells in 1968-69 without finding oil in the target Devonian Winnipegosis Formation.

A new area of gas production was also found during those years. The Beacon Hill gas field some 80 km north of the Lloydminster area began producing gas from 274 m depth in the Mannville Formation (Cretaceous) in 1963 and the adjacent Pierceland field was created in 1969. Together those fields have some 1686.7 X 10^6 m^3 of remaining reserves.

The decade of the seventies saw a drop in activity, with 6600 wells being drilled and some 45 new fields found. Twenty-seven of these were in the Lloydminster heavy crude area and there was no substantial new development in other regions. Several companies got together to run the Saskatchewan Heavy Oil Project (SHOP), which was an exploration program in western

Saskatchewan. It ran from 1978 to 1983 in the Kindersley area, during which time 110 exploratory wells were drilled. Several fields were found, including Luseland (Bakken, Mississippian) in 1979, and it was responsible for expanding the Cactus Lake heavy oil field in the Bakken/Basal Mannville (Mississippian/Cretaceous).

The most recent years, 1980 to 1990, have seen 19,415 wells drilled. The all-time record of 3851 was set in 1985. More than 40 new fields have been found and are distributed throughout the already defined areas. Moosomin and Red Jacket were found in 1984 east of the old (1952) Wapella field and in similar Jurassic and Cretaceous strata. They are producing medium crude from about 700 m depth. An increase in the number of deep (>2500 m) wells drilled in southeastern Saskatchewan during 1986 to 1990 has resulted in the discovery of over 1 x 10^6 m^3 of oil reserves in Devonian and Ordovician strata. In the Estevan - Macoun area, 32 wells have been completed in the Devonian Winnipegosis Formation. This activity was initiated by the drilling of Home *et al.* Tableland 8-22-2-9W2 which in its first full month of production in September 1986 produced 117 m^3/day of light oil from the Winnipegosis Formation at a depth of 2580 m. In the Minton area, renewed interest in deeper horizons was generated by the successful recompletion in 1989 of Mark *et al.* Minton 11-2-3-21W2 in the Winnipegosis Formation at a depth of 2610 m. This well had previously produced over 20 x 10^3 m^3 of light crude from the Ordovician Red River Formation. These Devonian and Ordovician oils are derived from kukersitic source rocks in the Red River Formation. To the end of 1990, seven additional wells have been completed in the Red River Formation and two in the Winnipegosis Formation.

Enhanced Recovery Projects

Even while new fields were being discovered and developed, production from older fields was being enhanced by techniques aimed at increasing recovery. The first of these secondary recovery operations was in the Dollard field of southwestern Saskatchewan where waterflood was applied to the Shaunavon (Jurassic) reservoir in March 1956. It was followed in that year by waterflood projects at the Fosterton, Gull Lake and Success oil fields. In September 1958, waterflood was applied to part of the Steelman field in southeastern Saskatchewan. Applications to other fields have continued ever since and at present some 103 waterflood projects are in operation.

In situ wet combustion was initiated in the Roseray reservoir at Battrum in November 1965. A similar technique has been applied since 1969 to the Aberfeldy Sparky (Cretaceous) reservoir and to the Fosterton Roseray reservoir since March 1970. A steamflood project started at Aberfeldy in 1981 and other experimental methods such as carbon dioxide flood are under development for use in various reservoir types throughout the province (Plate 3).

The amount of oil gained by enhanced recovery is extremely variable depending as it does upon the size of the reservoir as well as the oil and reservoir types. Actual increases vary from 0.10 percent of original oil in place for the non-unit Viking Sand in the Dodsland Field to 50.00 percent for Unit No. 1 of the Roseray Sand in the Suffield Field. The largest increase in the actual producible reserves is the 28.0 X 10^6 m^3 from the Midale Unit in the Weyburn Field (a 15.90 % increase of original oil in place).

Horizontal wells

The most recent innovative technology to be utilized in the recovery of Saskatchewan oil is horizontal drilling. Advances in drilling technology have made it possible to complete wells which have a conventional vertical component, an angled component and, within a reservoir, a horizontal component which may exceed 1000 m in length. The first horizontal well in Saskatchewan, Sceptre Murphy Tangleflags North C9C10-23-52-25W3, was drilled in the fall of 1987 as part of the Tangleflags North Steamflood Pilot, which was partially funded through the Canada-Saskatchewan Heavy Oil/Fossil Fuels Agreement. This well has a horizontal component of 406 m in a Lower Cretaceous Mannville heavy oil reservoir. Primary production from this well averaged 23 m^3 of oil/day. Following steam injection, the well produced a maximum daily average of 261 m^3 of oil in September 1990. A second horizontal well with a horizontal component of 500 m was drilled in 1990 as part of pilot expansion. The Saskoil Plover Lake enhanced recovery project (Section 5-35-26W3) will also utilize horizontal and steam injection wells. Six horizontal wells drilled in 1989 and 1990 have an average length of 569 m. These wells were completed in the Bakken Formation (Mississippian/Devonian) and are still on primary production in early 1991.

The majority of horizontal wells in Saskatchewan are not associated with enhanced recovery projects. In 1988 and 1989 eight such wells were completed in Mannville heavy oil reservoirs and four in Mississippian carbonate reservoirs. A dramatic increase in horizontal drilling in 1990 resulted in the completion of 43 Mannville wells, 27 Mississippian wells, one in the Viking Formation (Lower Cretaceous) and one in the Roseray Formation (Jurassic). The longest horizontal well in Saskatchewan is Coenerco et al Gainsborough North 15-32-2-30W1 which has a horizontal component of 938 m in the Mississippian Frobisher-Alida Beds. Maximum average daily production has been achieved by Sceptre Gainsborough North 3-5-3-30W1 which produced 327 m^3 oil/day in April 1990 from a 522 m horizontal section within the Frobisher-Alida Beds. Maximum average daily oil production from the best vertical wells in this area is <50 m^3.

Production and Reserves

For administrative purposes, the province is divided into four petroleum-producing areas. Area I is the most northerly and westerly, around Lloydminster. Area II is south of Area I, and covers the fields around Kindersley.

Plate 3. Clustered pumps to directionally drilled wells in a steamflood pilot project, Aberfeldy, Sparky reservoir.

Area III is the most southerly and westerly, thus encompassing those fields in the neighbourhood of Swift Current. Area IV is the southerly and easterly region, around Weyburn and district.

Reserves within each area are subdivided, if necessary, into heavy, medium and light crude. The figures in Table 2 give the production to the end of 1985 and the reserves remaining for each category and area. Gas is tabulated on a province-wide basis.

Table 2 - Petroleum and Natural Gas Reserves of Saskatchewan to end of 1989

	Oil (x 10^6 m^3)	
	Produced	*Remaining*
Area I (Heavy)	48.155	25.830
Area II (Heavy)	14.212	12.450
(Light)	18.838	7.120
Area III (Medium)	85.510	22.148
Area IV (Medium)	87.245	23.716
(Light)	116.486	27.999
Total Province	370.446	119.263
	Natural Gas (x 10^6 m^3)	
Total Province	50,514.2	79,788.6

Prospecting and Development Regulations

Mineral Ownership

At one time mineral rights were not recognized as separate and apart from surface rights, and the issue of a land grant meant that the land and the minerals under it were disposed of by the Crown. The Dominion and Imperial governments, in negotiating in 1870 with the Hudson's Bay Company for the surrender of its interest in Rupert's Land and the North West Territories, part of which was to eventually become Saskatchewan, made certain land grants to the company which included minerals other than gold and silver. The Dominion government made further land grants, which included mineral rights, to railway companies and to colonization companies and individuals in the early days of settlement.

In 1887 all new land grants west of the third meridian in the area that is now Saskatchewan were made subject to a reservation of minerals in the Crown, and in 1890 this was extended to the area east of the third meridian. When the Province of Saskatchewan was created in 1905, jurisdiction over natural resources was retained by the Dominion government and was not relinquished to the province until October 1, 1930. Between 1930 and 1939, the province inadvertently alienated additional Crown mineral rights during disposition of Crown lands to individuals when transfers of title did not specifically include reservation of minerals in the Crown.

The various transfers of Crown mineral rights have resulted in freehold mineral ownership of 32.3 million ha which, with few exceptions, is confined to and comprises about 24 percent of the area surveyed into townships and sections in the southern half of the province.

Prior to October 1930, the disposition of Crown minerals in Saskatchewan was under the jurisdiction of the federal government, and exploration and development were controlled by federal legislation. Following the transfer of natural resources to provincial control, the province implemented a Mineral Resources Act under which a series of mineral-specific regulations were formulated to govern disposition and exploration and development of Crown-owned minerals.

Exploration and development of minerals are currently governed under The Mineral Resources Act, 1985, which applies to all mineral resources in Saskatchewan, and The Crown Minerals Act which applies only to Crown-owned minerals.

Metallic and Precious Minerals

Prospecting for and the development of Crown-owned metallic and precious minerals are governed by The Mineral Disposition Regulations, 1986. The exclusive right to explore for minerals is granted through the issuance of claims which may range in size from 16 to 6000 ha. In the Precambrian Shield area of northern Saskatchewan, where most of this exploration takes place, these claims must be staked out on the ground. In the surveyed area of southern Saskatchewan claims are issued by map staking. A claim holder is guaranteed the right to take the claim to lease. Mineral leases have a renewable term of 10 years and are required for any mineral production. Mineral dispositions are kept in good standing by performing an annual minimum work expenditure and submitting reports documenting the results. When a mineral lease is brought into commercial production an annual rental is paid in lieu of the work expenditure requirement.

In certain instances, in areas of low activity, the minister may issue exploration permits which grant exclusive exploration rights to larger tracts of land, 10 000 to 50 000 hectares, for a two year period. The permit holder must meet prescribed work expenditure requirements and may convert any or all of the permit area into claims.

Industrial Minerals

The disposition of rights to Crown-owned industrial minerals is governed by four sets of mineral-specific regulations: The Coal Disposition Regulations, 1988, dealing with coal; The Alkali Mining Regulations, dealing with surface accumulations of soluble mineral salts, principally sodium sulphate; The Subsurface Mineral Regulations, 1960, dealing with soluble mineral salts occurring more than 200 (61 m) feet below the surface (i.e. bedded salt and potash minerals); and The Quarrying Regulations, 1957, dealing with defined quarriable substances including aggregates, clays and silica sand.

Under these regulations, dispositions are made by permits, which cover large areas for short terms for preliminary exploration purposes, and by leases for more detailed exploration or production. Alkali minerals are held only under lease. Permits are based on map descriptions and leases are staked out in unsurveyed areas and granted on the basis of legal land descriptions in the surveyed area. Permits are held by satisfaction of a work expenditure requirement and leases are held by an annual rental based on size.

For sand, gravel and structural clays, The Sand and Gravel Act deems these quarriable substances to belong to and pass with ownership of the surface. They are therefore deemed to be minerals and governed by The Quarrying Regulations, 1957, only where title to the surface is vested in the Crown.

Petroleum and Natural Gas

A person may apply for a 'permit' to explore for oil and gas in the province, under The Oil and Gas Disposition Regulations, for any area of land not exceeding 40 470 ha in respect of which the oil and gas rights are the property of the Crown. This permit grants the permittee the right, licence, privilege and authority to explore but not remove, produce or recover such oil and gas until a

lease pursuant to these regulations has been applied for and granted.

A permit is good for 3 years and renewable annually for 2 years; and for its maintenance the permittee is required to carry out exploration work to a value stipulated in the regulations, and to submit reports on work done, including copies of geophysical maps where geophysical surveys have been carried out.

In the event of a commercial discovery, the holder of the permit is required to take out a lease or leases within rectangular areas stipulated by the permittee in accordance with the regulations, and surrender rights to the remaining lands. The amount of permit area that can be leased ranges from 40 to 60 percent of Crown land in a township. Alternatively, on a first discovery in formations more than 12 miles (19.3) from a previous discovery, the first lease selection may range from 50 to 70 percent of the permit land in a township. The percentage increases with depth to the target producing formations (i.e., the pre-Devonian to the Cambrian).

At some point in the exploration phase, a company may elect to narrow its focus to one or more selected localities for detailed evaluation. In this case, it would take out a drilling reservation, which is essentially a permit less than 8094 ha in area. A condition for this reservation is the drilling of a well to a designated formation within a one-year period. Once the drilling commitment has been met, the holder of the reservation can select up to 50 percent of the acreage for leasing.

In petroleum prospecting, drilling and geophysical sensing, especially seismic shooting and logging of wells, are all activities requiring licences under The Oil and Gas Conservation Regulations and The Sedimentary Basin Geophysical Exploration Regulations.

Access to available Crown Lands for petroleum exploration is usually provided for by requests to Saskatchewan Energy and Mines that the land be put up for public tender. These, prior to land sales, are then advertized in the Saskatchewan Gazette with the data for receipt of sealed bids. The foregoing applies to applications for permits, drilling reservations and leases.

The Precambrian

Northern Saskatchewan is underlain largely by Precambrian rocks of varying metamorphic grade and deformation. At present knowledge, these rocks date from ca. 3070 to 3014 Ma ago to the Neohelikian (ca. 1450 to 1350 Ma), at which time the postmetamorphic sedimentary Athabasca Basin was formed.

Following the lead by Lewry and Sibbald (1977), the pre-Athabasca rocks have been divided into a number of lithostructural domains. These domains may be grouped into three main regions, namely the "Western Craton", the Cree Lake Zone and the Reindeer Zone, which in general terms represent distinctive remnant facets of a sector of the Lower Proterozoic Trans-Hudson Orogen. Later epeirogenic events continued on a local scale until at least Paleozoic times, some of them associated with uranium and other mineralization. Several debatable meteorite impact structures have been described, including the Carswell Structure in the Athabasca Basin and the Deep Bay structure on Reindeer Lake, which contains remnants of Cretaceous rocks.

The southern margin of the Shield is overlapped by subhorizontal Paleozoic and Cretaceous strata, and is generally poorly exposed. The Shield is glacially sculptured and overlain in places by extensive Quaternary glacial deposits. Relief is low, and the terrain is variably rugged, forested and lake-strewn, typical of large parts of the Canadian Shield in lower latitudes. The forest opens out to some extent north of Lake Athabasca, where the relief locally reaches over 200 m.

The geology of northern Saskatchewan is described under the following main headings (Figure 6):

1) "Western Craton";
2) Cree Lake Zone;
3) Reindeer Zone;
4) Athabasca Basin;
5) Post-tectonic Features; and
6) Quaternary Geology.

The "Western Craton": Western Foreland to the Trans-Hudson Orogen

The Western Craton - as originally defined by Lewry and Sibbald (1977) - is that part of the Shield lying west of the Virgin River and Black Lake Shear Zones. In regional terms, it is an extension of the Keewatin Zone (Hoffman, 1984) which underlies neighbouring parts of the Northwest Territories. The craton is exposed north and south of the Athabasca Basin and in the window of the circular Carswell Structure. Limited information is also available from drill core taken beneath the Athabasca Group. The craton is described under two headings:

1) Southern Region; and
2) Northern Region.

Southern Region

The terrain south of the Athabasca Basin is almost entirely underlain by rocks of the Western Granulite Domain (Lewry and Sibbald, 1977) which comprises a variety of felsic (charnockitic to enderbitic) through to mafic (noritic) rocks with granulite or retrogressed granulite facies mineral assemblages characterized by blue quartz. Other rock types include pelitic gneisses and distinctive garnetiferous felsic gneisses of supracrustal aspect. Preliminary U-Pb dating indicates a minimum age of ca. 2290 Ma (Bickford *et al.*, 1986).

The Western Granulite Domain also includes the Clearwater Anorthosite. Layered mafic plutons in the craton may be associated with these anorthosites (Collerson and Lewry, 1985). Preliminary U/Pb zircon dating of the anorthosite gives an emplacement age of ca. 2000 Ma (Bickford *et al.*, 1986). The southwestern margin of the domain is progressively more sheared towards the bounding Virgin River Shear Zone. In places along this margin, there are also swarms of late mafic dykes and sills (Wallis, 1970). The poorly exposed Firebag Domain (Lewry and Sibbald, 1977) to the west features similar lithological assemblages to those of the Western Granulite Domain.

The Clearwater Domain, which lies between the Western Granulite and Firebag Domains, comprises granitoid rocks of which the Clearwater Granite is the most prominent. Wilson (1986) has identified a similar granitoid terrain (the Wylie Lake Granitoid) under the Alberta portion of the Athabasca Basin.

Northern Region

The Greater Beaverlodge area, centred around Uranium City, has been intensely studied because of its gold and uranium deposits since World War II, and is probably a key to an understanding of neighbouring terrains. A number of domains have been recently proposed (Figure 7) for the northern region (Gilboy, 1981; Macdonald, 1983), which modify the earlier subdivisions of Beck (1969).

The region has been subdivided into several cratonic blocks made up predominantly of Archean rocks which are generally bounded by mylonitic shear zones. Intervening terrains generally contain reworked Archean and/or Lower Proterozoic rocks. The Archean rocks are commonly similar to those of the Western Granulite Domain, and mineral assemblages are also generally typomorphic of retrogressed granulite facies. As pointed out by Sibbald (1987), these cratonic blocks are generally coincident on aeromagnetic maps with areas of relatively high magnetic relief.

Archean Blocks

The Dodge and Tantato Domains comprise a variety of partially retrograded granulite facies mafic to felsic rocks. Little information is available on their possible

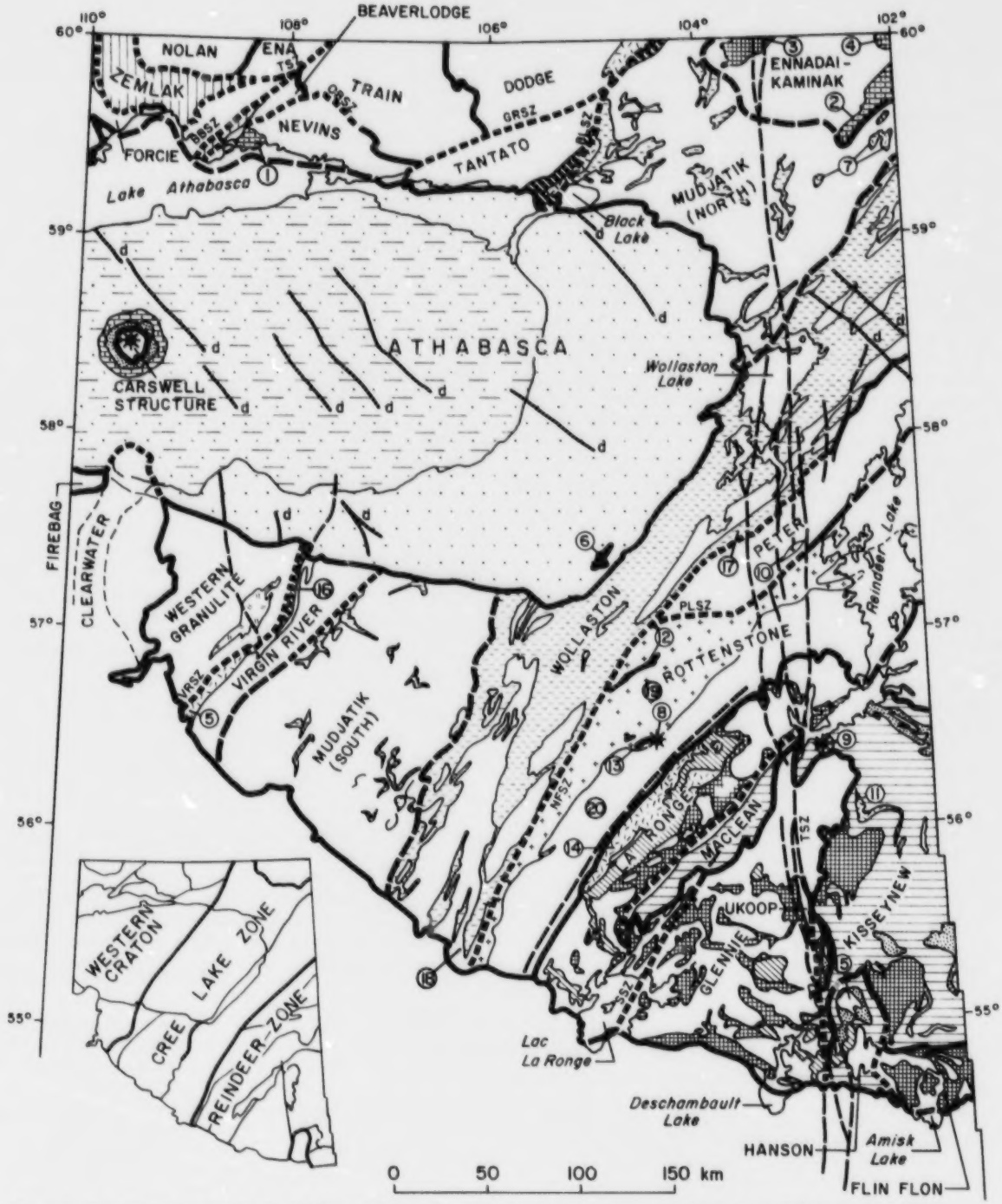


Figure 6 - Geological map of the Saskatchewan Precambrian Shield. Domain names are shown in capitals in abbreviated form.

Numbered features: 1, Murmac Bay Group; 2, Many Islands Group; 3, Ennadai Group; 4, Hurwitz Group; 5, Junction Granite; 6, Moore Lakes Complex; 7, Fluorite-bearing late granites; 8, Gow Lake Impact Structure; 9, Deep Bay Impact Structure; 10, Campbell River Group; 11, Harriot Lake Enderbites; 12, Dobbin Lake Dykes; 13, Tremblay Lake Dykes; 14, Hickson Lake Pluton; 15, Sahli Granite; 16, Virgin River Schists; 17, George Lake area; 18, Meyers and Duddridge Lakes area; 19, Wathaman Batholith; 20, Rottenstone (tonalitic) migmatites.
Shear zones: BBSZ, Black Bay; TSZ, Tazin; GRSZ, Grease River; OBSZ, Oldman-Bulyea; BLSZ, Black Lake; VRSZ, Virgin River; NFSZ, Needle Falls; PLSZ, Parker Lake; SSZ, Stanley; TSZ, Tabbernor.

ATHABASCA GROUP (Neohelikian):

Carswell and Douglas Formations

Fair Point, Lazenby Lake, Wolverine Point, Locker Lake, Otherside and Tuma Lake Formations (marine clastics)

Manitou Falls Formation (terrestrial clastics)

WESTERN CRATON and ENNADAI-KAMINAK DOMAIN

Many Islands/Hurwitz Groups (ca. 1800 Ma?)
Murmac Bay Group (bracketted ca. 3070-2350 Ma)

Cataclasized graben/"successor basin" zones (ca. 1800 Ma basin infill)

Clearwater Anorthosite (ca. 2000 Ma)

Greenstones (ca. 2680 Ma)

Undivided (largely Archean, except for Train Lake Domain)

CREE LAKE ZONE (Ensialic)

Supracrustal rocks, largely Wollaston Group (probably Aphebian)

Felsic gneisses (presumed Archean)

REINDEER ZONE (Ensimatic - Lower Proterozoic/Hudsonian)

Granitoid terrain

Greenstones (Aphebian)

Metagreywacke-psammopelite (Kisseynew type); garnetiferous biotite gneisses±hornblende

Metagreywacke-psammopelite (other domains); biotite gneisses± hornblende (metaconglomerate)

Metapsammite/meta-arkose

Felsic pluton (Wathaman Batholith)

GENERAL

Other notable felsic pluton

Meteoritic impact structure

Domain boundary

Domain boundary, where major mylonitic zone

Mylonitic shear zone or major fault

Basic dyke or intrusion (mainly post-Helikian)

Basic dyke swarm (along Virgin River and Black Lake Shear Zones)

precursors. Biotitic gneisses of possible sedimentary origin are more prominent in the Dodge Domain. Thick bands of noritic rocks (hypersthene-bearing mafic granulites) and garnetiferous felsic gneisses occur in the Tantato Domain. The two domains are separated by the major Grease River Shear Zone. The Chipman Sill Swarm (Macdonald, 1980) forms a zone, up to 2 or 3 km wide along the Black Lake Shear Zone, demarcating the southeastern boundary of these domains, in similar style to the southeastern margin of the Western Granulite Domain to the south.

Although radiometric dates are lacking, these domains are presumed to be Archean. The major part of the Nevins Lake Block comprises retrogressed assemblages: felsic gneisses, garnetiferous gneisses and mafic gneisses with rare quartzite. Preliminary Rb-Sr dating indicates a minimum (probable metamorphic) age of 2631±130 Ma for a hypersthene gneiss, and a younger event at 2315±60 Ma for a garnetiferous felsic gneiss (Bell and Blenkinsop, 1984). To the west in the Greater Beaverlodge area, the metamorphic grade is lower and a supracrustal assemblage, the Murmac Bay Group, has been recognized. This miogeoclinal-type assemblage includes metaquartzites, garnet and biotite schists, metaconglomerates, dolomitic marble and pillowed metabasalt. A basement to this group has been recently found in the Lodge Bay Granite, dated by the U-Pb zircon method at ca. 3070 to 3014 Ma (Van Schmus *et al.*, 1986).

The Nolan Block comprises plutonic rocks with well-defined U-Pb zircon ages of ca. 2581 to 2639 Ma (Van Schmus *et al.*, 1986). This is the only terrain known in northern Saskatchewan to produce K-Ar ages in the range 2500 to 2300 Ma (Bell and Macdonald, 1982), indicating significant internal stability of the block since Archean times.

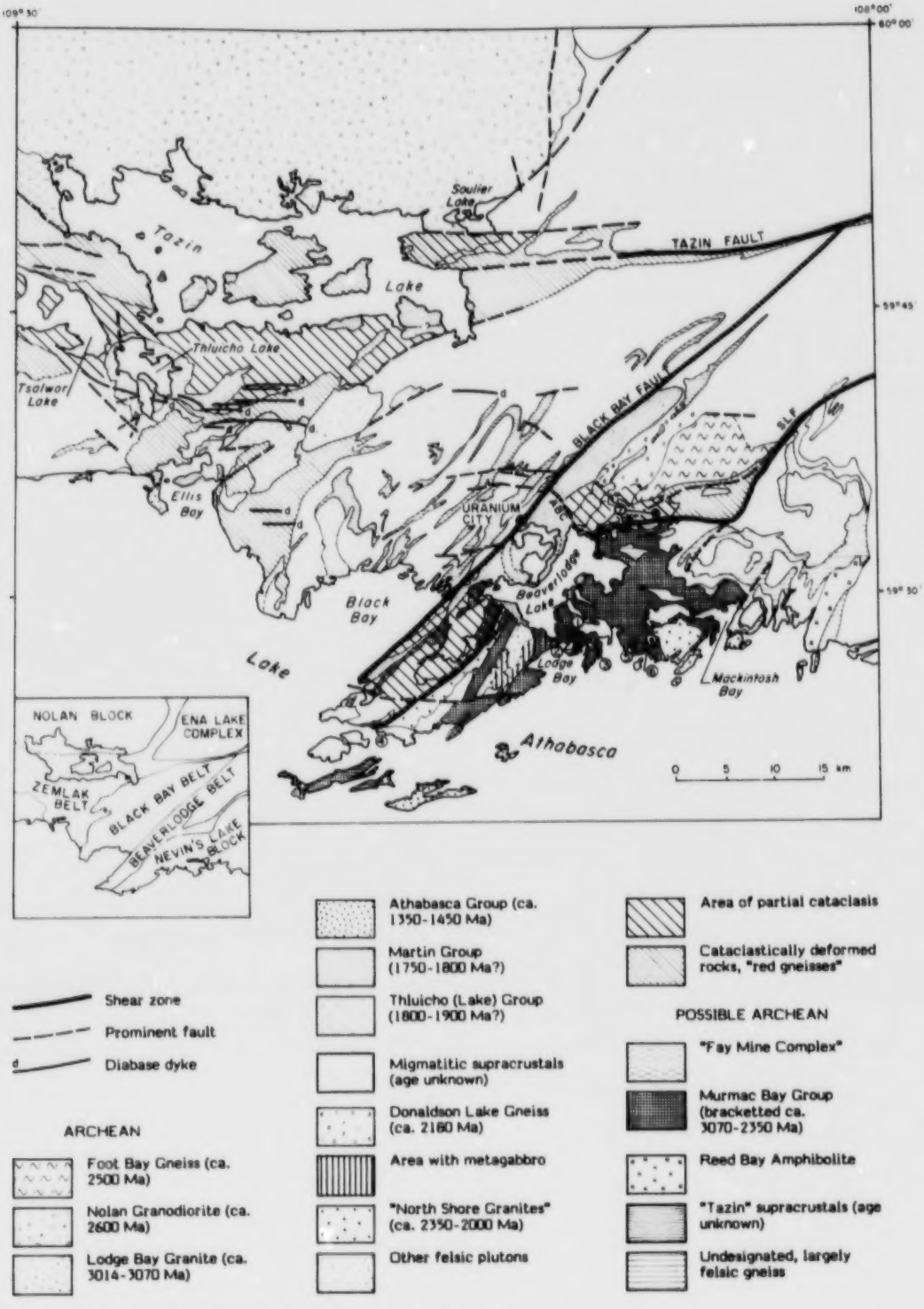


Figure 7 - Geology of the Greater Beaverlodge area and environs.

1, Frontier Granite; 2, Box (Mine) Granite; 3, Athona Granite; 4, Gunnar Granite; 5, Nicholson Bay; 6, Fishhook Bay; 7, site of Fay-Ace-Verna Mine (Eldorado); SLF, St. Louis Fault; ABC, ABC Fault. See text for references to age dating.

Remobilized Belts

The remobilized belts exhibit a variety of features ranging from magmatic to cataclastic. The Greater Beaverlodge area has been affected by multiple reactivations since Lodge Bay Granite times some 3000 Ma ago (Table 3). In the Goldfields - Nicholson Bay area, the Murmac Bay Group is intruded by the auriferous "North Shore Plutons", dated by the U-Pb zircon and Rb-Sr methods at ca. 2350, 2180 and 2000 Ma. Some of these plutons appear to show classical metasomatic features. The role of the Foot Bay Gneiss and the structurally overlying migmatitic Donaldson Lake Gneiss, with U-Pb zircon dates of ca. 2500 and 2180 Ma respectively, is imperfectly understood.

The Beaverlodge Cataclastic Belt, lying immediately southeast of the Black Bay Fault, is the remnant of an irregularly mylonitized and fractured graben into which post-metamorphic redbeds of the Martin Group were deposited. A similar, but more extensive graben system occurs further west, rimming the Nolan Block and underlying much of the area between Tazin Lake and Lake Athabasca. Within this system, the Martin Group is underlain by the Thluicho Lake and Ellis Bay Groups in a basin sequence. Although no age has been determined for these successor basin groups, they were probably laid down during and immediately following the main Hudsonian cycle (ca. 1900 to 1800 Ma ago).

The Train Lake Domain is largely migmatitic and granitic, and there is no evidence of an earlier Archean history. This domain coincides with Darnley's (1981) regional "Athabasca Axis" marked by negative gravity, high radiometric anomalies and low magnetic signature. Preliminary Rb-Sr dating gives an age of 1950±125 Ma (Bell and Blenkinsop, 1984).

Table 3 - Geochronology, Greater Beaverlodge Area and Environs

Approximate Dates (Ma)[1]	*Nolan Block*	*Nevins Lake Block*		*Inter-block Terrain*	*Train Lake Domain*	*Mineralization*
		West	*East*			
1350-1450		Athabasca Group				
1415				Gabbro sill		
1495				Basic dyke		
1750-1800?				Pegmatite		Initial pitchblende
1800-1900?				Martin Group Thluicho Lake Group		Later syngenetic uraninite
1950±125*					Quartzofeldspathic gneiss	
1994±37*		North Shore Granites:				Gold?
2000		Box Granite Metasomatic (Box) phase				
2181±5*		Gunnar Granite				
2179±12*				Donaldson Lake Gneiss		
2200						Early syngenetic uraninite
2315±60			Garnet-feldspar gneiss			
2327±17*		Mackintosh Granite				
2356±14*		Athona Granite				
2350-2450	Cooling (K-Ar)					
2513±30*			Foot Bay Gneiss			
2581-2639*	Nolan Granodiorite and assoc. plutons					
		Murmac Bay Gp[2]				
2631±130			Hypersthene gneiss			
3070-3014*		Lodge Bay Granite				

Notes: (1) Some date ranges are approximate. For references see text.
* Dates are based on U-Pb zircon determinations. Double lines indicate recognized unconformities.
(2) The Murmac Bay Group is bracketted ca.3014-2356 Ma, and is probably equivalent to the Fay Mine complex.

Cree Lake Zone: Remobilized Ensialic Miogeoclinal Zone to the Trans-Hudson Orogen

Included in this section of the Cree Lake Zone are the more anomalous Ennadai-Kaminak and Peter Lake Domains. The Cree Lake Zone itself has been divided into three domains: the Mudjatik, Virgin River and Wollaston.

Mudjatik Domain

The central and most extensive part of the zone, the Mudjatik Domain, is dominated by felsic gneisses which are considered to be essentially Archean infrastructure. These gneisses are mostly granitoid, but locally show gneissic and laminated features suggestive of a possible supracrustal origin. Unambiguous supracrustal rocks, including metapelites, amphibolites and local iron formation, occur in narrow arcuate bands throughout the Mudjatik Domain, defining regional-scale domes, which Lewry and Sibbald (1980) have interpreted as migmatite lobes. Attained metamorphic grades are generally in the amphibolite-granulite facies transition.

Virgin River Domain

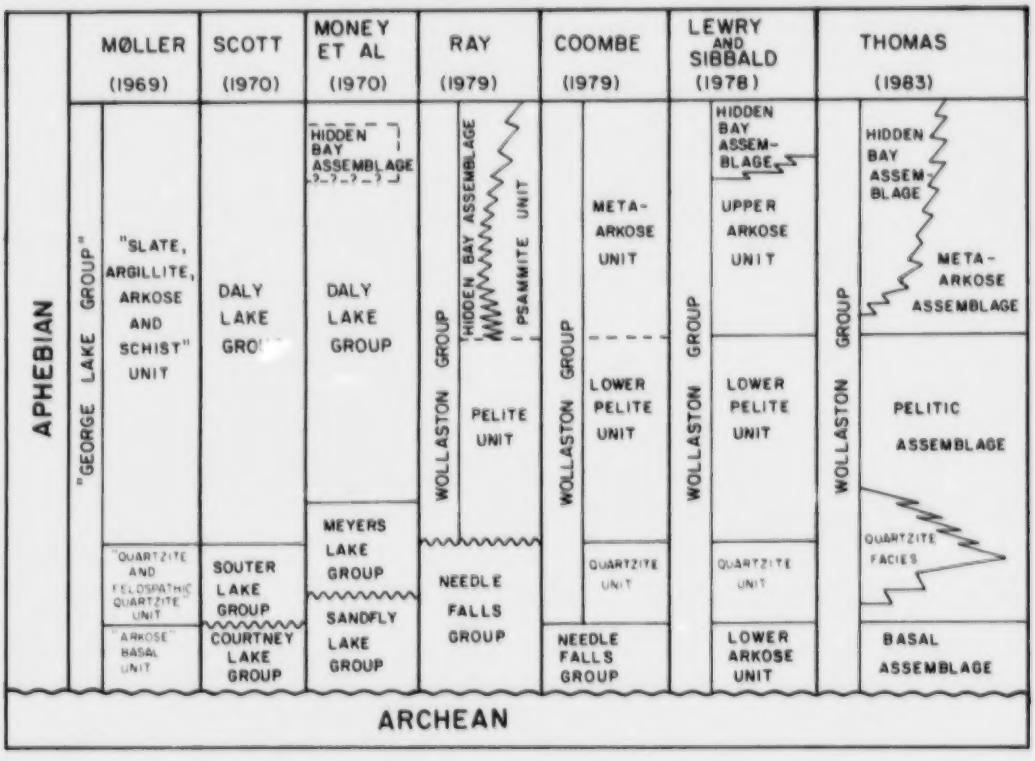
The margins of the Cree Lake Zone feature northeasterly fold trends with elongate mantled gneiss dome structures. The Virgin River Domain to the west is dominantly a granitoid terrain – in which structures are picked out by thin bands of supracrustal rocks – and, along the western boundary, a belt of greenstones and associated supracrustal rocks (the Virgin River Schists). The Junction Granite, lying immediately southeast of the Virgin River Shear Zone (to which it appears to be genetically related), has been dated by the U-Pb zircon method at ca. 1820 Ma (Bickford *et al.*, 1986) and by the Rb-Sr method at 1720±45 Ma (Bell and Macdonald, 1982).

Wollaston Domain

The Wollaston Domain, to the east, is dominated by the supracrustal rocks of the Wollaston Group. A number of stratigraphic successions have been proposed, depending on location and interpretation (Table 4).

Basal quartzites and quartz pebble conglomerates also are found in places along the southeastern margin of the Wollaston Domain at Meyers Lake and Duddridge Lake. Basal pelites are commonly graphitic, forming a thin layer immediately overlying a tectonically modified unconformity with the felsic gneisses. Meta-arkoses are the dominant lithological component. The Hidden Bay Assemblage is developed only in the Wollaston Lake area.

Table 4 - Comparative Stratigraphic Successions in the Wollaston Domain.



The underlying immature arkoses and amphibolites (possibly mafic volcanics) of Scott's (1970) Courtney Lake Group and Coombe's (1979) Needle Falls Group, which are exposed in thin strips along the Needle Falls Shear Zone at the eastern boundary of the Cree Lake Zone, belong to a possible early rift valley sequence. There is current uncertainty over correlation and nomenclature for this assemblage.

The Cree Lake Zone has been interpreted by Lewry and Sibbald (1977) as derived by intense pervasive and extensive remobilization of the Archean cratonic foreland during the Hudsonian cycle (Figure 8).

Radiometric work on the felsic gneisses is inconclusive, although a "scatterchron" of ca. 2500 Ma has been indicated (Bell and Blenkinsop, 1979). Hudsonian remobilization is also indicated in some of the granitoid rocks (e.g. Ray, 1980). Although no ages are available, the Wollaston Group is generally considered to be Aphebian at ca. 2400 to 2000 Ma. Lewry and Sibbald (1980) have suggested that supracrustal rocks in the Mudjatik Domain may also include Archean as well as Aphebian material.

Ennadai-Kaminak Domain

The Ennadai-Kaminak Domain is virtually unmapped in Saskatchewan, and its boundaries are only broadly estimated. The Ennadai Group (Macdonald, 1984) is part of a major belt of metavolcanics and metasediments which extends into the Northwest Territories through Snowbird Lake and probably correlates with the Kaminak Group (Stockwell, 1964; Taylor, 1963). Deformation is relatively low and the metamorphic grade is lower amphibolite facies. Contiguous granitic rocks appear to be high-level plutons, and there is no indication of a basement. The Ennadai Group in Saskatchewan has yielded a U-Pb zircon age of 2682±5.9 Ma (Chiarenzelli and Macdonald, 1986). The Many Islands Group in the east has been correlated with the Hurwitz Group of probable Aphebian age (Munday, 1973b). According to Lewry (1979a), the Many Islands Group overlies an infrastructural front developed from a granitoid, and presumed Archean basement.

Peter Lake Domain

The Peter Lake Domain is predominantly a bimodal plutonic complex bounded to the northwest by the Needle Falls Shear Zone and to the southeast by the Parker Lake Shear. Towards Manitoba, the southeastern margin of the domain is less distinct. Mafic-ultramafic plutons with platinum group metal affinity and probable Archean age (the Swan Lake Gabbro; Ray and Wanless, 1980) are an important component. These include locally well-layered rocks of subalkaline continental type (Watters, 1983), as well as alkaline intrusives. The domain features remobilized granitoid gneisses resembling those in the Cree Lake Zone (Ray, 1979; Stauffer *et al.*, 1981). Homogeneous and little-deformed felsic granitoids are, however, more common; radiometric dating suggests that these are related to the neighbouring Wathaman Batholith of ca. 1865 Ma age.

The Campbell River Group (Lewry, 1977) occupies a narrow belt within the domain. This low-grade assemblage includes slates, phyllites, arenites with minor chert and mafic metavolcanic rocks. The age and relations of the group are uncertain.

Reindeer Zone: Ensimatic Arc-Interarc Zone of the Trans-Hudson Orogen

The Reindeer Zone (Stauffer, 1984) is a complex region of eugeoclinal volcanic arc, plutonic and interarc greywacke-pelite assemblages which are considered to have occupied the region between two convergent continental plates in this sector of the Trans-Hudson Orogen. Radiometric determinations have produced Lower Proterozoic dates, largely in the range 1880 to 1800 Ma (e.g. Van Schmus *et al.*, 1987). The generally ensimatic nature of the zone is indicated by 1) the absence of older basement dates, 2) published $^{87}Sr/^{86}Sr$ initial ratios, 3) petrochemistry of the igneous rocks, and 4) neodymium isotope studies (e.g. Bell and Macdonald, 1982; Watters and Armstrong, 1985; Stauffer *et al.*, 1975; Watters, 1985; Walker and Watters, 1982; Chauvel *et al.*, 1987). Some of these studies suggest, however, a minor Archean crustal component in the northwestern part of the zone. The Reindeer Zone is bounded largely on the northwest by the Needle Falls Shear Zone.

Several workers (e.g. Lewry and Sibbald, 1980; Macdonald and Broughton, 1980) have divided the Reindeer Zone into a number of domains and belts which, although reflecting distinctions in lithostructural assemblages, probably do not everywhere adequately portray the genetic relationships of the major rock units (Figure 9).

Plutonic Facies: The Rottenstone Domain

The Rottenstone Domain in the northwestern part of the Reindeer Zone is dominantly plutonic. The Wathaman Batholith (Fumerton *et al.*, 1984) is part of a major late-tectonic pluton that is more extensively developed in Manitoba, where it is known as the Chipewyan Batholith. In Saskatchewan, compositions are generally uniform in the range monzogranite to quartz diorite. Large sections of the batholith are potassium feldspar megacryst quartz monzonite, and the only variation over extensive areas is in the amount and size of the megacrysts. The northwestern margin is marked largely by the Needle Falls and Parker Lake shear zones, the latest phases at least of which postdate the batholith (Ray, 1980). Northeastwards towards Manitoba, Wathaman-type granitoids intrude gneisses of the Peter Lake Domain. Radiometric dating by both Rb-Sr and U-Pb zircon methods gives an unequivocal intrusive age of ca. 1870 to 1860 Ma for the Wathaman Batholith (Ray and Wanless, 1980; Bell and Macdonald, 1982; Van Schmus *et al.*, 1987).

The Rottenstone Migmatite Belt is a zone of intimately interfingering tonalite-trondhjemite intrusions and supracrustal rocks. These paleosomes comprise up to about 15 percent of the terrain regionally and are mainly psammitic to psammopelitic metagreywackes similar to

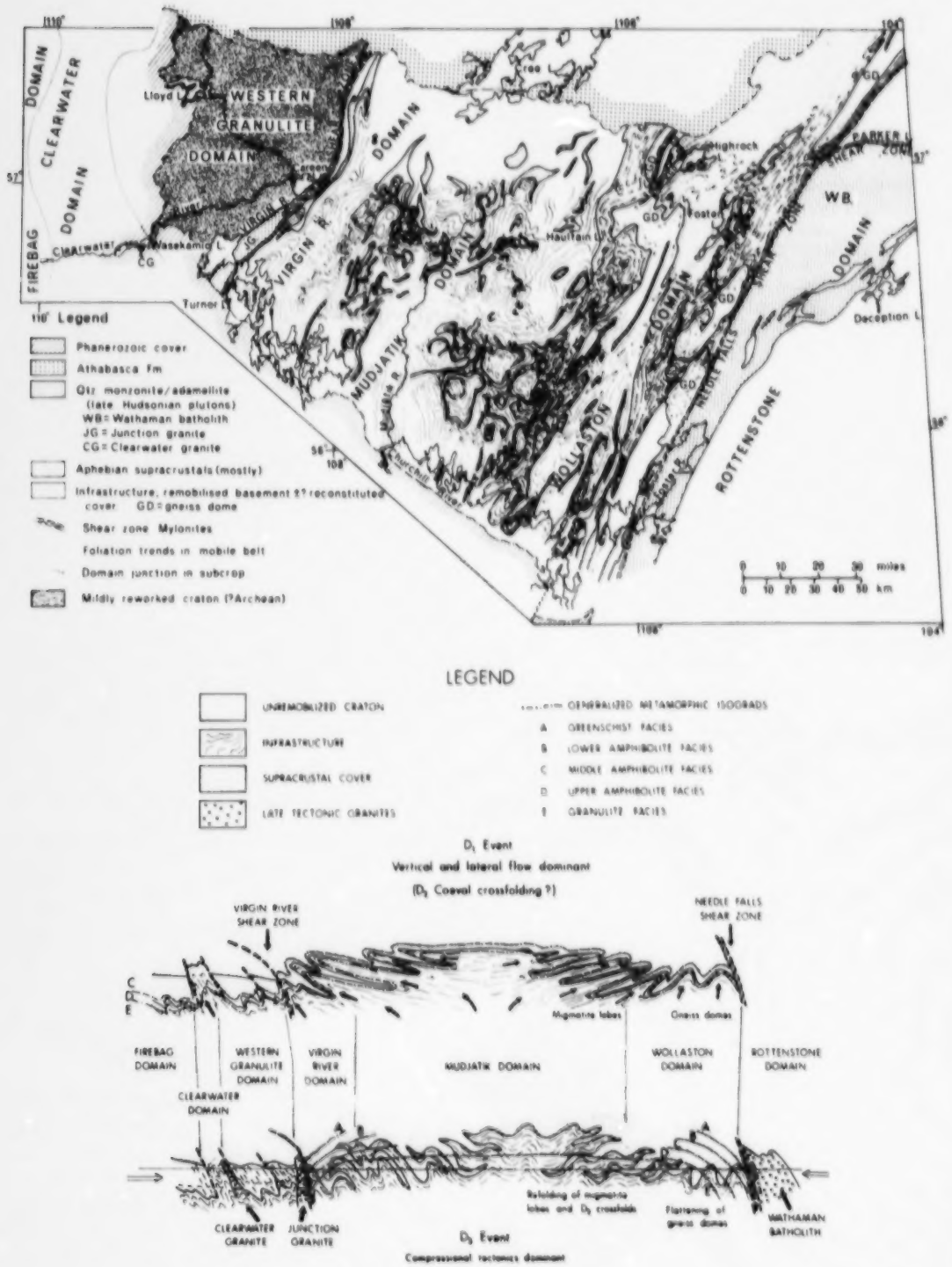


Figure 8 - Schematic interpretation of the southern part of the Cree Lake Zone (after Lewry and Sibbald, 1980): (Top) Geological map; (Bottom) Geological cross-section.

those in the adjacent La Ronge Domain to the southeast. Multiple intrusive and deformational phases can be recognized in the complex. Lewry *et al.* (1980, 1981) has distinguished four main neosomal suites ranging from quartz diorite-tonalite to late pink granitic aplopegmatites.

Arc Facies of the Southeastern Domains

La Ronge Domain

The Central Metavolcanic Belt (Coombe *et al.*, 1986) of the La Ronge Domain, which is continuous to the northeast with the Lynn Lake Greenstone Belt in Manitoba, includes a broad range of volcanic and volcaniclastic rocks to which the name La Ronge Group may be given. Mafic to intermediate varieties are the most common (e.g. Harper, 1986; Thomas, 1985b, 1986), signifying a departure from bimodal assemblages found in other greenstone belts. Disposed in a general regional westerly-younging homocline, the lower part of the succession includes komatiitic to bonninitic ultramafic rocks, probably both extrusive and intrusive. Metamorphic grades are generally lower amphibolite facies and there is very little pervasive regional deformation. A variety of discrete medium to small meso- to epizonal plutons occur (Harper *et al.*, 1986) and earlier, probably basement-derived plutons occur in the southern part of the belt (Thomas, 1986). Geochemical studies on the volcanics reveal a preponderance of low-potassium tholeiitic to calc-alkaline rocks, suggesting that the arcs developed on oceanic crust close to and possibly including a continental margin, and that the associated plutons are derived by melting and fractionation of lower volcanic material (Watters, 1981, 1984, 1985, 1986).

Radiometric determinations by the U-Pb zircon method have given ages in the range of 1876 to 1882 Ma and 1834 to 1866 Ma for the volcanic and plutonic rocks, respectively (Bickford *et al.*, 1986).

The southeastern margin of the Central Metavolcanic Belt is generally marked by the McLennan Lake Tectonic Zone, a northwesterly dipping belt of high strain and partial mylonitization (Lewry, 1983; Thomas, 1985a, b). Some of the smaller shear zones transecting the belt are mineralized with gold, and are the focus for current gold exploration.

The Central Metavolcanic Belt is flanked to the northwest by the Crew Lake Belt, comprising mainly volcanogenic metagreywacke probably shed off the La Ronge arc in a back arc position (Lewry, 1984). The northwestern margin of the Crew Lake Belt merges in an injection zone into the Hickson Lake Pluton and migmatites of the Rottenstone Domain.

The Central Metavolcanic Belt is terminated to the northeast and southwest respectively by the Numabin Complex and the La Ronge Horseshoe terrain. These relatively high metamorphic grade and dominantly plutonic complexes may be interpreted as infrastructural arches exposing deeper crustal levels.

Relatively fresh greenstone assemblages occur immediately east of the La Ronge Horseshoe in the Sulphide-Hebden-MacKay Lakes area (e.g. Sibbald, 1986; Slimmon, 1986; M.W. Thomas, 1986). This terrain, which is regarded as a segment of the Central Metavolcanic Belt, is the scene of exploration on account of a number of stratabound gold occurrences.

Glennie Lake Domain

Metavolcanogenic rocks occur in narrow arcuate belts of the Glennie Lake Domain, and granitoid gneisses and granitoids are preponderant over supracrustal rocks. Deformation is generally more intense than in the La Ronge Domain, and metamorphic grades are typically amphibolite facies.

Lewry (1984) identified a major, generally shallow-dipping, high strain detachment zone (the "Guncoat Gneisses") which separates an upper tectonic assemblage (the "Wapassini Allochthon") from an underlying "Iskwatikan Subdomain". Another regionally significant high strain zone is expressed in the "Nistowiak Gneisses". The entire thrust plate package, including early plutons, was considered to have been subsequently refolded and intruded by later plutons, as displayed in the Laonil Lake region. The upper plate thrust sequences have been interpreted by Lewry as rooting in the La Ronge Domain to the northwest. The implied consanguinity with the supracrustal rocks of the La Ronge Domain may not, however, be fully borne out by the preliminary petrochemical studies from the Laonil Lake area, which indicate a wholly ensimatic (tholeiitic) arc derivation (G.D. Delaney, pers. comm.).

Although the Glennie Lake Domain was first tentatively regarded as an older block (Macdonald, 1975a) or even a possible Archean microcontinent (Lewry, 1981), subsequent radiometric work has not confirmed this hypothesis (e.g. Bell and Macdonald, 1982; Van Schmus *et al.*, 1987). Volcanic rock U-Pb zircon ages are similar to those obtained from the La Ronge Domain at ca. 1870 Ma and the plutons range from ca. 1852 to 1836 Ma. The Caroll Lake Gneiss, originally considered to be possible (Archean) basement, has yielded only a slightly older age of 1893±35 Ma (Van Schmus *et al.*, 1987).

Tabbernor Zone

The eastern boundary of the Glennie Lake Domain is in part defined by the Tabbernor Zone, which includes the Ukoop Lake Segment, a "straight belt" of tight north-south periclinal folds and strong metamorphic gradients, and the Tabbernor Fault, which is a major continuous mylonitic shear zone merging into later brittle faulting with regional sinistral horizontal displacement (Macdonald, 1976). North of Laird Lake, the Tabbernor Zone is represented only by later shear and brittle faults, and the domain boundary is less well defined.

Stanley Shear Zone

The western boundary of the Glennie Lake Domain is represented by the Stanley Shear Zone, a subvertical

belt of mylonites and tectonic schists, and by late brittle faults (Lewry, 1981). This zone is probably less fundamental in nature than the Tabbernor.

Flin Flon Domain

Volcanogenic rocks of the Amisk Group are bimodal in composition, predominantly calc-alkaline and overlain by molasse-type clastics of the Missi Group (Stauffer *et al.*, 1975; Walker and Watters, 1982; Parslow, 1984). There is little regional penetrative deformation, and the metamorphic grades rarely exceed greenschist facies. The volcanic assemblages were intruded by plutons of pre- to immediately post-Missi age between ca. 1880 and 1800 Ma ago (Sangster, 1972; Bell and Macdonald, 1982; Watters and Armstrong, 1985; MacQuarrie, pers. comm., 1973).

Inter-Arc Terrains: Kisseynew Domain and MacLean Lake Belt

The Kisseynew Domain and the MacLean Lake Belt are metasedimentary terrains interpreted as basins infilled by greywacke deposits largely shed off the volcanic arcs. "Kisseynew-type" rocks are mostly represented by pelitic to psammopelitic garnet-biotite gneisses and metagreywackes. Metamorphic grades attained granulite facies in many places, anatexis is prevalent, and regional pervasive ductile deformation is more intense than in neighbouring terrains.

MacLean Lake Belt

The MacLean Lake Belt largely comprises volcanogenic greywackes (the MacLean Lake Gneisses). Polymict fanglomerates are also common. An overlying sequence of molasse-type meta-arkoses (the McLennan Group) closes to the southwest in a major overturned synform (the Haugen Lake Synform). Meta-arkoses occur in a more or less continuous strip northeastwards across the northern flanks of the Kisseynew basin into the Sickle Group meta-arkoses of Manitoba.

The meta-arkoses of the McLennan Group abut directly against the Central Metavolcanic Belt along the northwesterly dipping McLennan Lake Tectonic Zone. Lewry (1984) argued that the Central Metavolcanic Belt is thrust over the meta-arkoses from an original lower stratigraphic position, as demonstrated by the overturned Haugen Lake Synform. In the Milton Island area farther north, however, meta-arkoses were observed to stratigraphically overlie the volcanics (Sibbald, 1971).

The MacLean Lake Gneisses grade up to transitional granulite facies and are generally highly deformed. Lewry (1984) regards the MacLean Lake Belt as a "telescoped" remnant of a fore-arc basin.

Kisseynew Domain

Some of the pelitic to psammopelitic rocks in the Kisseynew Domain have been referred to as the Nokomis Group. More recent terminology has borrowed the term Burntwood Supergroup from Manitoba. True stratigraphic thickness is unknown, as the rocks are considered to be repeated and contorted by strong overfolds, nappes and thrust sheets (Pearson, 1972b; Macdonald, 1975b; Ashton and Wheatley, 1986). The Attitti and Scimitar Lake Complexes contain a high proportion of volcanogenic rocks. Persistent bands of mafic and calc-silicate bearing rocks can be traced many kilometres in the southeastern part of the domain; one of these has been referred to as the "Kisseynew Metallotect" (by extrapolation from Manitoba, Gale and Ostrey, 1984) on account of anomalous metal concentrations, including gold (Parslow and Gaskarth, 1985). In the north-central part of the domain, there are large volumes of anatectic granodiorite and every gradation between diatectites, metatectites and granodiorites.

Psammitic gneisses and meta-arkose, which locally contain abundant sillimanite, have been equated with the Sickle gneisses of the Lynn Lake Belt and the Sheridan rocks of Manitoba, as well as with the Missi Group in the Flin Flon Domain. Ashton and Wheatley (1986) have, moreover, proposed a correlation between the Amisk Group and the Nokomis. The relation between the Kisseynew and Flin Flon rocks has been debated for many years. It seems probable that the distinction is a function of deformation and differences in tectonic and depositional environments northwards into the deep basin of the Kisseynew. Although generally regarded as Aphebian, no definitive radiometric information is yet available for the Kisseynew rocks in Saskatchewan.

Figure 9 *(Right)* - Outline geology of the major part of the Reindeer Zone.

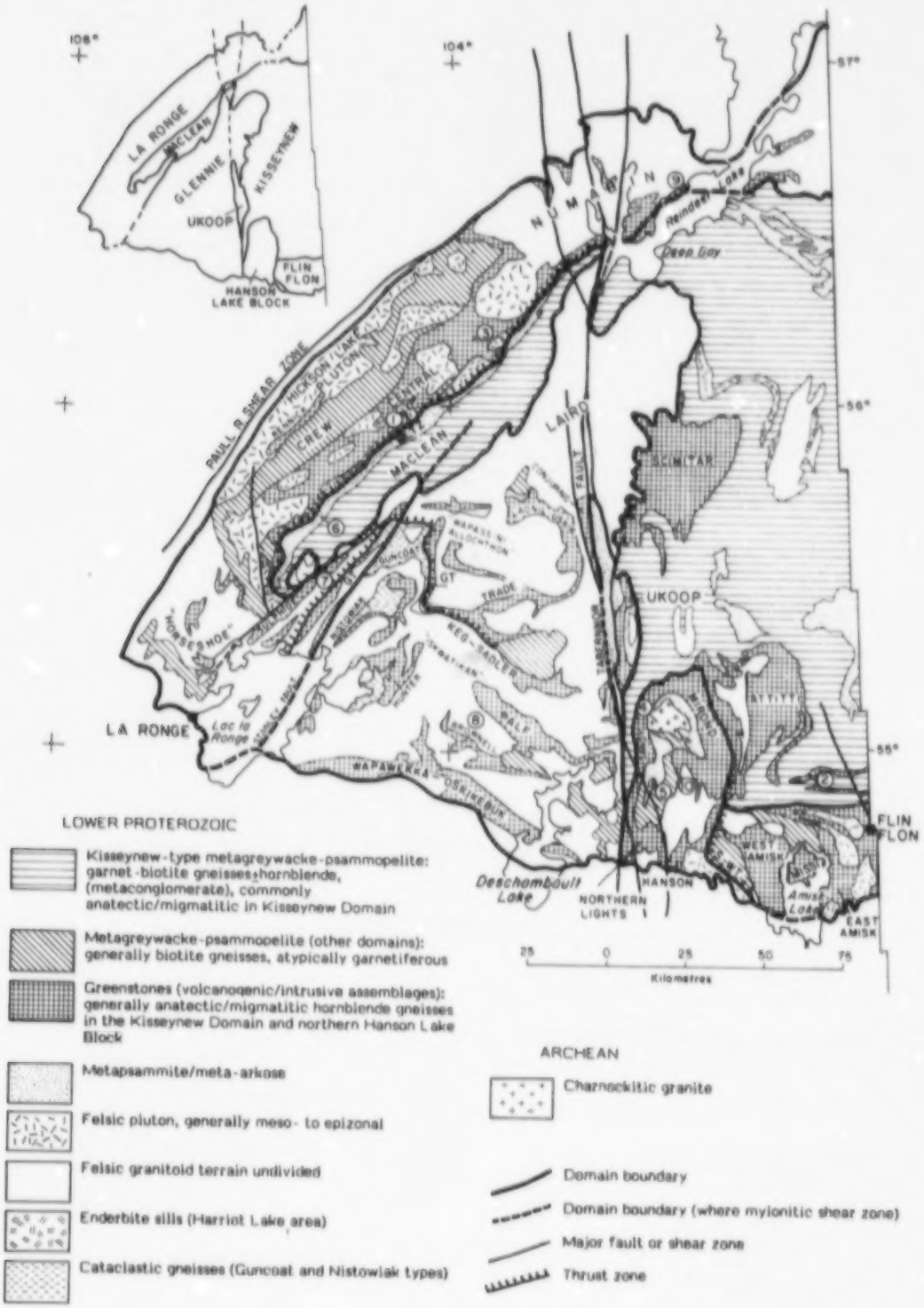
Numbered locations: 1, Star Lake Pluton; 2, "Kisseynew Metallotect"; 3, Waddy Lake section; 4, Sahli Granite; 5, McMillan Point Granite; 6, McLennan Group; 7, Bridgeman Lake Pluton; 8, Caroll Lake Gneiss; 9, Milton Island area; 10, Jan Lake.

Domains/subdomains: Kisseynew = Kisseynew Domain; MacLean = MacLean Lake Belt; Glennie = Glennie (Lake) Domain; Ukoop = Ukoop Lake Segment; La Ronge = La Ronge Domain; Crew = Crew Lake Belt; Numabin = Numabin Complex; Horseshoe = La Ronge Horseshoe terrain; Iskwatikan = Iskwatikan Subdomain; Laird = Laird Lake Complex.

Greenstone belts: Central = Central Metavolcanic Belt; Rennick = Rennick Lake; Sulphide = Sulphide-Hebden-MacKay Lakes; Guncoat; Hunter = Hunter Bay; Wapawekka-Oskikebuk; Brownell = Brownell Lake; Palf = Palf Lake; Keg-Sadler = Keg-Sadler Lakes; Trade = Trade Lake; Laonil-Uskik = Laonil-Uskik Lakes; Conjuring = Conjuring River. Flin Flon greenstone regions: West Amisk; Missi (Island); East Amisk; Hanson = Hanson Lake Volcanics; Northern Lights = Northern Lights Volcanics.

Hornblendic gneiss complexes (volcanogenic): Scimitar = Scimitar Lake Complex; Attitti = Attitti Lake Complex; Sandy = Sandy Narrows; Mirond = Mirond Lake.

Shear zones or thrusts: MLTZ = McLennan Lake Tectonic Zone; S-WT = Sturgeon-Weir Thrust; GT = Guncoat Thrust.


108°
104°
57°
56°
55°
LA RONGE
MACLEAN
GLENNIE
KISSEYNEW
UKOOP
FLIN FLON
HANSON LAKE BLOCK
PAULL R. SHEAR ZONE
HICKSON LAKE PLUTONIC
CREW
MACLEAN
LAIRD
FAULT
NUMA
Reindeer Lake
Deep Bay
SCIMITAR
UKOOP
"HORSESHOE"
TRADE
KEG-SADLER
RALF
ATTITYY
WAPAWEKKA
OSKIKEBUR
LA RONGE
Lac la Ronge
Deschambault Lake
NORTHERN LIGHTS
HANSON
WEST AMISK
Amisk Lake
EAST AMISK
FLIN FLON
25 0 25 50 75
Kilometres
LOWER PROTEROZOIC
Kisseynew-type metagreywacke-psammopelite: garnet-biotite gneisses±hornblende, (metaconglomerate), commonly anatectic/migmatitic in Kisseynew Domain
Metagreywacke-psammopelite (other domains): generally biotite gneisses, atypically garnetiferous
Greenstones (volcanogenic/intrusive assemblages): generally anatectic/migmatitic hornblende gneisses in the Kisseynew Domain and northern Hanson Lake Block
Metapsammite/meta-arkose
Felsic pluton, generally meso- to epizonal
Felsic granitoid terrain undivided
Enderbite sills (Harriot Lake area)
Cataclastic gneisses (Gunncat and Nistowiak types)
ARCHEAN
Charnockitic granite
Domain boundary
Domain boundary (where mylonitic shear zone)
Major fault or shear zone
Thrust zone

The Harriot Lake Enderbite units, which occur in the central part of the domain, were considered by Gilboy (1976) to represent large sills involved in Hudsonian folding. Rb-Sr dating, however, indicates a relatively young age of 1525±80 Ma (Bell and Macdonald, 1982).

Hanson Lake Block

The Hanson Lake Block (Macdonald and MacQuarrie, 1978; MacQuarrie, 1979; Macdonald, 1981; Macdonald *et al.*, 1986) is separated from the Glennie Lake Domain by the Tabbernor Fault in the west and from the Flin Flon Domain by the Sturgeon-Weir Thrust in the east. The block comprises metavolcanics, metavolcaniclastics, meta-arkoses, granitoid rocks and the Sahli Granite, a distinctive charnockitic granite. In the south, where metamorphic grades are low, the metavolcanogenic rocks resemble those in the Flin Flon Domain. Metamorphic grades and deformation are higher in the north where the boundary with the Kisseynew rocks is obscured by complexly refolded westerly-verging thrust sheets. The Sahli Granite has yielded late Archean dates (Bell and Macdonald, 1982; Van Schmus *et al.*, 1987) and it, and the similar McMillan Point Granite nearby, have been postulated as Archean mantled-gneiss dome inliers (Macdonald, 1974; Macdonald *et al.*, 1986). Coleman (1970) obtained a near Archean Rb-Sr isochron from a suite of mixed volcanics and granites from the Hanson Lake area in the southern part of the block, but an individual sample from one of Coleman's sites has yielded Hudsonian ages by the Pb/Pb and Pb/U zircon methods (Sangster, 1972; Van Schmus *et al.*, 1987). The age of the majority of the supracrustal rocks in the Hanson Lake Block is therefore currently uncertain.

The Hanson Lake Block contains conspicuous post-tectonic aplopegmatitic sheets termed the Jan Lake Granite. Rb-Sr dating has given a tentative age of 1580±60 Ma for this suite (Bell and Macdonald, 1982). Beryliferous pegmatites close by along the Sturgeon River are probably related.

Athabasca Basin

Athabasca Group

The postmetamorphic Athabasca Group comprises fluvial to marine clastic sediments deposited during the

Table 5 - Outline Geological Chronology of the Reindeer Zone, Saskatchewan Precambrian Shield [1]

Approximate Dates (Ma)[2]	*Rottenstone Domain*	*La Ronge-Glennie Domains*	*Peter Lake Domain*	*Hanson Lake Block*	*Flin Flon Domain*[4]
1580				Jan Lake Granite [6]	
1780				Sahli Granite [5]	"Hudsonian Orogeny"
1800					Post-Missi intrusions
1800-1810					Missi Group
1810-1835					Pluton sequence
1834-1866		Mesozonal plutons			
1837		Numabin Tonalite			
1860			"younger granite"		
1863	Migmatitic neosome				
1865-1875	Wathaman Batholith				
1865			"younger gabbro"		
1885					
1976-1882		La Ronge Group (volcs)			
1888				Hanson Lake Volcs	
1893		Caroll Lake Gneiss			
2500				Hanson Lake Volcs [3]	
2500				Sahli Granite	
2538			Swan River Gabbro		
2556-2582			"older granite gneiss"		

Notes (1) No reliable dates are yet available from the MacLean Lake Belt and the Kisseynew Domain
(2) Dates quoted in this table are referenced in the text. Except where otherwise indicated all dates are based on U/Pb zircon determinations
(3) The Hanson Lake Volcanics date of ca. 2500 Ma (Coleman, 1970) may indicate an earlier group
(4) MacQuarrie (1977)
(5) Nd-Sm mineral dates
(6) Rb-Sr dates
(7) Double line indicates recognized unconformity

Paleohelikian 1450 to 1350 Ma ago (e.g. Ramaekers, 1980a, 1980b, 1980c, 1980d, 1981). The group covers about 100 000 km^2 in Saskatchewan and a small part of eastern Alberta. The central part of the basin is about 1400 m thick. Apart from faulting and local thrust folding, the group is undeformed and is probably largely resting at initial shallow dips. It has also been conjectured that the basin corresponds fairly closely with its original limits (Figure 10).

Although the group was originally termed the Athabasca Sandstone (Fahrig, 1961) and consists largely of hematitic quartz arenites and conglomerates, other rock types are also important. Ramaekers (1980c) has subdivided the group into a lower regressive fluvial sequence (the Manitou Falls Formation, covering the perimeter and eastern side of the basin) and a number of subsequent generally transgressive marine sequences (Table 6).

Conglomerates predominate at the base of the terrestrial units and there is a general upward fining of the sediments. Tuffs and phosphatic units occur in the upper part of the Wolverine Point Formation. Dolomites of the Carswell Formation are exposed around the Carswell Structure in the west.

The Athabasca Group lies unconformably on a generally well-weathered basement regolith as much as 50 m or more thick. Where this regolith is coincident with features such as graphitic basement rocks, post-Athabasca faulting and basement topographic ridges, the contact zone tends to be accentuated by clayey alteration haloes which in places serve as prime locations for unconformity-type uranium mineralization (Sibbald, 1985).

Table 6 - Summary Stratigraphic Succession, Athabasca Group

Marine	*Fluviatile*
8. Carswell Fm: Stromatolitic and oolitic dolomite	
7. Douglas Fm: Black, red and green mudstones, siltstones and sandstones	
6. Tuma Lake Fm: Mainly pebbly sandstone	
5. Otherside Fm: Sandstone, minor siltstone	
4. Locker Lake Fm: Mainly pebbly sandstone	
3. Wolverine Point Fm: b. Mainly siltstone and clay-rich sandstone, phosphoritic, tuffaceous a. Mainly sandstone, minor siltstone	
2. Lazenby Lake Fm: Mainly pebbly sandstone, sandstone	
1. Fair Point Fm: Mainly pebbly to (partly equivalent) cobbly sandstone	
	1. Manitou Falls Fm: Intraclast-rich sandstone, sandstone, conglomerate, pebbly sandstone, minor conglomerate

Sub-Athabasca Basement

The geology of the sub-Athabasca basement has been studied by Gilboy (1982a, 1983). Drill core information is limited to a perimeter zone 10 to 20 km wide. The Virgin River - Black Lake Shear Zone, which forms the southeastern boundary of the Western Craton, can be traced in the subsurface by means of the 1:250 000 aeromagnetic maps. The Western Craton region has a distinctively higher magnetic relief and intensity, corresponding to areas of mafic granulite facies rocks. Areas of flatter relief are equated with garnetiferous felsic units similar to those north and south of the basin. Granitic rocks of the Clearwater type are not conspicuous. Extensive areas of Wollaston-type metaarkoses underlain by metapelites have been encountered in drill holes in the southeastern perimeter of the basin. Conjectured Archean domal structures are more common towards the Virgin River - Black Lake Shear Zone.

Post-tectonic Features

Dykes and Late Intrusions

Large diabase-gabbro sills which cut the Wathaman Batholith northeast of Dobbin Lake and east of Tremblay Lake have been assigned a "probably Neohelikian/Hadrynian" age (Ray, 1983a). The Moore Lakes Complex on the southeastern perimeter of the Athabasca Basin comprises diabase-gabbro dykes, basement and Athabasca Group sediments; the dykes are dated at ca. 1100 to 1200 Ma (Ramaekers, pers. comm.).

Local post ca. 1880 Ma dyke swarms have been identified in several parts of the Shield, in number probably proportional to the detail of mapping. Major post-Hudsonian diabase dyke systems are the Beaverlodge Dykes north of Lake Athabasca (estimated at ca. 1450 Ma) and the Cree Lake Dykes along the southeastern margin of the Athabasca Basin (estimated at 1400-1100 Ma).

Fault and Fracture Systems

Late brittle fractures and faults commonly follow major shear zones, and may also be recognized through drainage patterns and topographic features. Regional fracture patterns are discernible on a local scale, as for example, in the Central Metavolcanic Belt, where they form parallel or conjugate systems with the McLennan Lake Tectonic Zone and, in some cases, sites for gold mineralization.

A more regional system of north-trending faults and master fractures is present in the eastern part of the Shield. It is typified by the Tabbernor Fault system, which can be traced both north into the Northwest Territories and south beyond the Shield in drainage patterns to beyond Cumberland House.

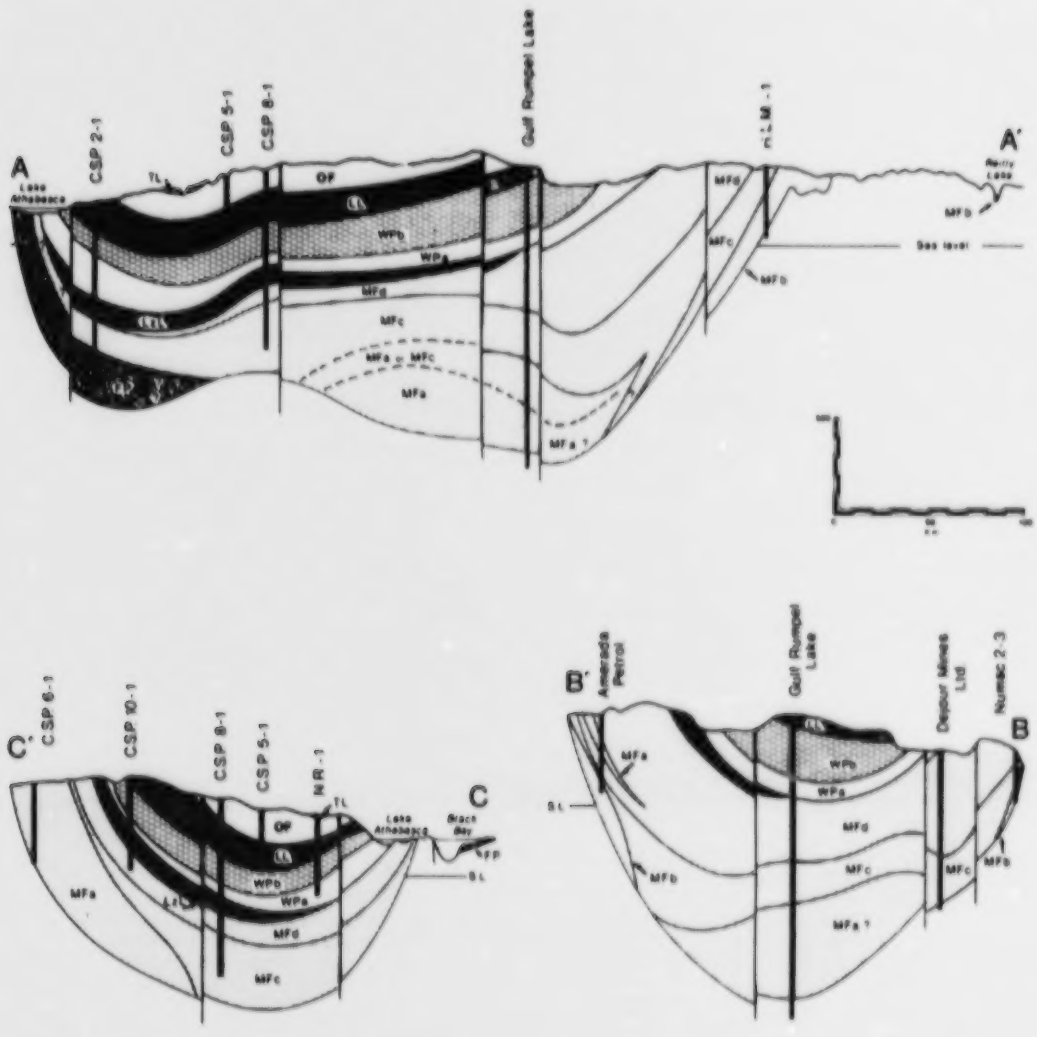
Figure 10 - Outline stratigraphy of the Athabasca Basin: *(Above)* Outline geological map; *(Facing page)* Geological cross sections.

Fracture systems are particularly conspicuous in the Greater Beaverlodge area, where they are in places associated with pitchblende veins.

Meteorite Impact Structures

A number of features in the Saskatchewan Shield have been identified as meteorite impact structures, although none of them without controversy. The largest of these is the Carswell Structure in the western part of the Athabasca Basin (Harper, 1982). This approximately circular structure is about 35 km wide in diameter, and exposes the Carswell and Douglas Formations at the outer annulus. Older Athabasca rocks of the William River Subgroup form an inner ring; these are in places highly disturbed, inverted and thrusted, presumably due to impact. An uplifted basement core about 18 km in diameter is faulted both tangentially at the perimeter and by offsetting radial faults. The basement and Williams River Subgroup rocks are intruded by the Cluff Breccia, which is generally considered to be an impact rock (Robertson and Grieve, 1975). Other evidence for impact includes the morphology of the structure, deformation lamellae in quartz, shatter cones and fractured cobbles (e.g. Currie, 1967; Pagel, 1975; Tapaninen, 1975, 1976). Impact is estimated to have occurred during the Ordovician ca. 478 Ma (Currie, 1967).

The Deep Bay Structure at the southern end of Reindeer Lake is about 10 km wide (Gilboy, 1980; Johnston, 1983). Cretaceous rocks have been recovered from drill holes under the lake.



The Gow Lake Structure is only about 5 km in diameter (Gilboy, 1982). Parts of the uplifted core, exposed as Calder Island, are underlain by impact rocks, namely karnaite (fine cherty lava-like material) and suevite (rubbly "pyroclastic" rock) (Robertson and Grieve, 1975).

Quaternary Geology

The Quaternary geology of the Shield area in Saskatchewan was mapped at reconnaissance scale during the seventies, and the results are summarized by Schreiner (1984).

Ice flow directions are generally towards the southwest. Features produced by the ice sheets are affected to a large extent by the nature of the underlying bedrock. Erosion of the pre-Helikian basement terrain has picked out major shear zones, faults and master fracture systems. The relatively rugged area north of Lake Athabasca is essentially stripped of overburden, and similar stripped terrain exists in the south-central part of the Shield in a belt stretching over to Reindeer Lake.

Over the Athabasca Basin, erosion of the relatively soft sandstones has produced thick ground moraines composed of sandy till, and extensive drumlins, eskers and outwash deposits occur. Drainage patterns tend to be dendritic, in contrast to a more trellised pattern over the pre-Helikian basement.

Several advances of the ice sheets produced a number of till horizons in some areas (e.g. Johnston, 1971, 1978), which are best preserved in lee positions to the ice flow. The observable striations, grooves, flutings, rôche moutonées and drumlins record the latest ice advance. Eskers, ice-walled channels, kettles and moraines produced during the last ice retreat are particularly common in the northern part of the Shield. A major ice-frontal position is represented by the

prominent Cree Lake Moraine which crosses the central part of the Shield.

During the last deglaciation (ca. 11,000 to 8,000 B.P.), lake deposits were built up in Lake Agassiz, and to a lesser extent in glacial Meadow Lake, glacial Cree Lake and glacial Lake Athabasca. As the ice retreated, the Lake Agassiz shore advanced from the southeastern part of the Shield northwards over Reindeer Lake to northeastern Saskatchewan. Glaciolacustrine offshore clay-silt and strand deposits are mainly encountered in the area underlain by Kisseynew rocks.

Postglacial eolian features, such as sand-blasted boulders, loess and sand dunes are found in some areas, the last-mentioned especially on the northern margins of the Athabasca Basin. Permafrost is encountered in low-lying peat bogs, particularly north of latitude 58°N.

The Phanerozoic

The Precambrian igneous-metamorphic terrain south of the Churchill River system descends below the erosional front of the Phanerozoic in a south-southeasterly direction into the Williston Basin of North Dakota. This basement is monoclinal, but is relieved by monadnocks, lineaments and scarps, and it slopes at a rate of 2.0 to 3.8 m/km. At the northern arc of the Williston Basin, this rate steepens to between 7.6 and 9.5 m/km, and the surface underlies 3200 m of Phanerozoic strata at the border with the United States (Figure 11).

Major subparallel gravity bands trend north and northwest from the Williston Basin (Figure 12) and are interpreted as the extension of domains on the shield to the north. The North American Central Plains Conductivity Anomaly is a belt of high electrical conductivity traceable to the Wollaston Domain from Wyoming (Camfield and Gough, 1977). It is postulated to be a suture marking plate boundaries. Likewise, the Nelson River gravity high is attributed to the boundary between the Churchill and Superior provinces.

Both static and dynamic effects of basement structures are detectable by their influence on stratigraphic con-

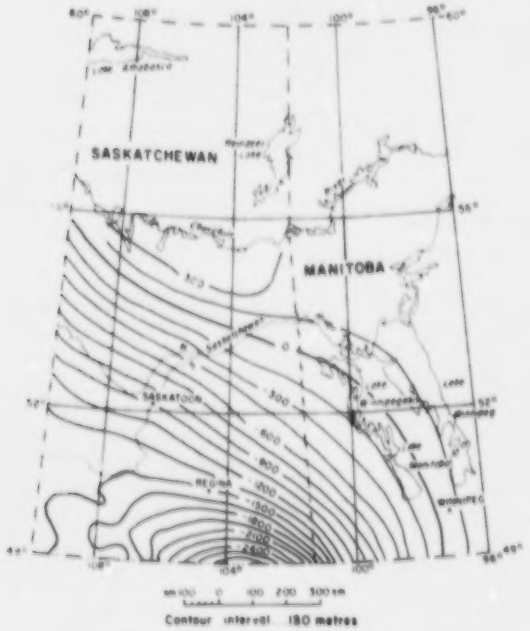


Figure 11 - Structure map of the Precambrian basement, Saskatchewan Manitoba.

Figure 12 - Tectonic map of Saskatchewan.

trols in the Phanerozoic strata. Thus the Meadow Lake Escarpment, which is traceable towards the Stanley Shear Zone, terminates to the southeast, the Lower Devonian Elk Point Basin of Alberta. The Nelson River gravity high is detected by sedimentational and erosional anomalies in the Paleozoic and Lower Cretaceous. This is also true of the Swift Current Platform to the west. Likewise, the several major linears influenced depositional styles, the movement of formation waters, and the creation of structures by focussing the solutioning of Devonian salt at various localities.

The stratigraphic succession may be divided into three lithologic classes:

1) Cambro-Ordovician sandstones and shales;
2) Ordovician to Mississippian carbonate-evaporites; and
3) Mesozoic and Cenozoic clastics dominated by sandstones, shales and mudstones with some coal.

The Paleozoic

Sandstones, siltstones and shales of the Earlie and Deadwood Formations (Cambrian) and Winnipeg Formation (Ordovician) comprise the basal clastic unit of the Phanerozoic in Saskatchewan except to the north of the Meadow Lake Escarpment in the northwest where Early Devonian erosion removed them and bared the Precambrian surface. The basal Phanerozoic unit in that area is the Middle Devonian Meadow Lake Formation. The Cambrian thickens westward towards its depocentre in southern Alberta, reaching over 490 m at the Alberta-Saskatchewan border, and thins to zero in eastern Saskatchewan north of 50°N latitude. In contrast, the Winnipeg Formation has a maximum thickness of 67 m in southeastern Saskatchewan and thickens southward to its depocentre in the Williston Basin which has its centre in North Dakota. The formation thins to the north and west and is not present in western Saskatchewan. The contact between the Cambrian and Ordovician clastic units represents a continent-wide hiatus.

The carbonates of the Ordovician and Silurian represent deposition in similar environments and a significant hiatus between the systems is not evident. They include the Red River, Stony Mountain and Stonewall Formations for the one part and the Interlake Group for the other. These strata, by virtue of their arcuate isopachs, centre on a greatly expanded Williston Basin, and thicken from an erosional edge to more than 440 m (Figure 13). The northwestern erosional front is aligned with the Meadow Lake Escarpment.

Stratigraphy

Dominant lithologies are dolomitic limestones and dolostones with mudstone to wackestone textures. Cyclic sedimentation associated with increasing basin salinity characterizes most Ordovician and lower Interlake strata (Kendall, 1976). Fully developed cycles consist of i) an argillaceous dolomite mudstone marker bed ii) a fossiliferous wackestone or mudstone unit, iii) a slightly argillaceous laminated mudstone unit, and iv) an anhydrite unit (Kendall, 1976). Anhydrites commonly cap cycles in Ordovician strata in southern Saskatchewan but in the Interlake Formation evaporites are present only in the deepest portion of the Williston Basin in North Dakota (Osadetz and Haidl, 1989). Overlying the cyclic deposits of the lower Interlake is a sequence dominated by dolomite mudstones with interbeds of dolomitized skeletal-peloidal wackestones and packstones and lesser coral-stromatoporoid boundstones and floatstones (Haidl, 1987). The uppermost Interlake strata preserved in southeastern Saskatchewan are dolostones which have been subjected to periodic subaerial exposure and vadose diagenesis. These rocks are characterized by brecciated textures, erosion surfaces, fenestral fabrics and abundant dolomite cements (Haidl, 1987; Magathan, 1987).

A continental hiatus separates the Late Silurian from the Middle Devonian. The Devonian sequence is also punctuated by local or intrabasinal unconformities marked by redbeds. Northwest of the Meadow Lake Escarpment, lowermost Middle Devonian strata open into Alberta and the Northwest Territories as the Lower Elk Point Subgroup of dolomite, shale, anhydrite and salt (Meadow Lake Formation). Four phases of cyclic lithologies characterize the remainder of Middle and Upper Devonian strata in Saskatchewan.

Each cycle sequentially comprises red beds, carbonates and evaporites. In the first phase, a component is a formation, thus the Ashern (shale), Winnipegosis (dolomite and limestone) and Prairie (salt and anhydrite) Formations. In the later phases, two or more components are

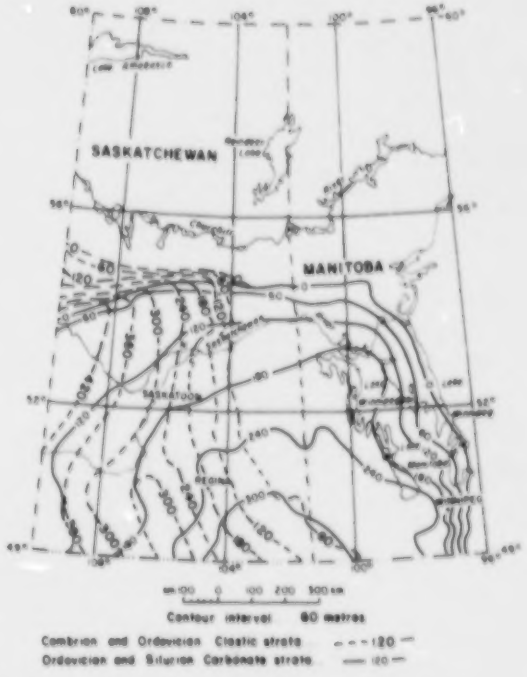


Figure 13 - Isopach map of Cambro-Ordovician clastics (dashed lines) and Ordovician and Silurian carbonates (solid lines).

included in a formation. The argillaceous bed of each cycle is represented by red and green dolomitic mudstone or argillaceous dolomite with patches of anhydrite and breccia. Carbonates are fine-grained limestone or dolomitic limestone containing brachiopods, corals, disarticulated crinoids, ostracodes and algal nodules. These deposits formed many reefal banks in the Winnipegosis. Evaporites are largely halite and anhydrite, and in the Prairie Formation also include sylvite and carnallite. This salt bed is up to 180 m thick (Figure 5).

The second phase is initiated by the Dawson Bay red bed, carbonate and salt, succeeded by the transgressive Souris River alternating sequence of fossiliferous limestone, thin anhydrite and halite, calcareous shale and argillaceous limestone. This last component becomes thickest near the top of the formation.

The Saskatchewan Group comprises the Duperow and Birdbear Formations. It represents the third phase, which is dominated by 90 to 150 m of crystalline limestone with a variety of carbonate facies that include skeletal and nonskeletal calcareous sand and mudstone. Minor thin anhydrite, local concentrations of halite and thin argillaceous limestone and calcareous shale also occur.

Red beds with breccia of dolomite and anhydrite, succeeded by green and black shale, characterize the Three Forks Group of the fourth phase.

Overall, the Devonian succession attains a thickness greater than 720 m in the axial portion of the Elk Point Basin. This thickness is somewhat reduced by considerable dissolution of the salt beds in the southwest of the province (Figure 14).

The Mississippian strata thicken from their semicircular subcrop edge southward to 550 m at the United States border (Figure 15). The carbonate strata overlie a basal sandstone and black shale unit (Bakken) that is traceable across the continent from the Rockies to the Appalachians. The carbonates represent a time-transgressive series which young westward. In the southeast, seven marker beds of argillaceous or arenaceous carbonate rocks delineate seven units termed "Beds", of which only the Midale, Ratcliffe and Poplar are regionally recognizable.

A basin facies of cherty, poorly fossiliferous, argillaceous and shaly limestone and calcareous laminite of bituminous and nonbituminous limestones (Souris Valley) succeeds the Bakken and grades eastward into mixed bioclastic limestones. The beds above the Souris Valley grade west to east as transgressive sequences of calcareous mudstone, crinoidal bioclastic carbonate, mixed bioclastic carbonate, oolitic carbonate and anhydrite mixed with halite (Figure 16).

The crinoidal bioclastic and the mixed bioclastic facies contain brachiopods, crinoids, corals and bryozoa forming skeletal calcareous sands cemented by sparry calcite or organic debris in a micritic matrix. They differ in

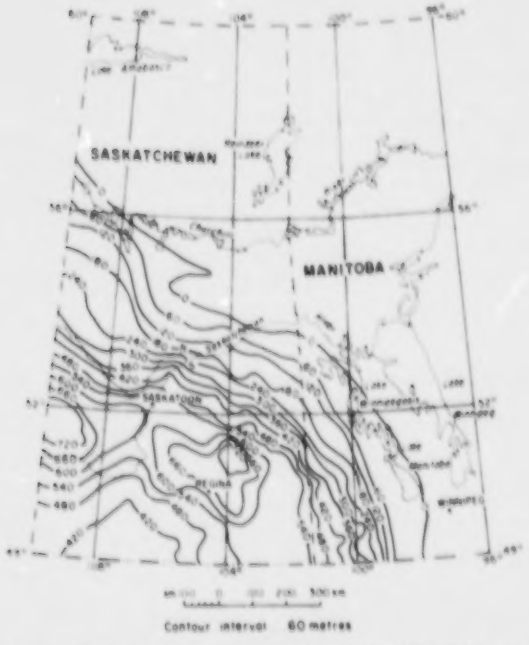


Figure 14 - Isopach map of Devonian strata, Saskatchewan and Manitoba.

Figure 15 - Isopach map of the Mississippian System (solid lines) and the Jurassic System (grey lines), Saskatchewan and Manitoba.

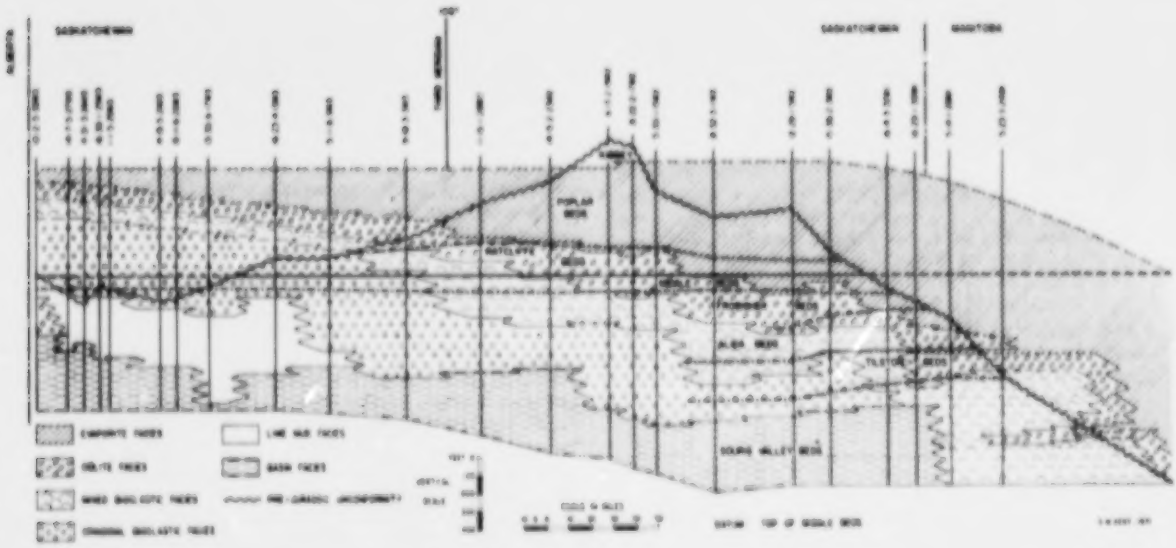


Figure 16 - East-west diagrammatic stratigraphic cross-section of the Mississippian in Saskatchewan and Manitoba (after Kent, 1971).

that the crinoids are dominant in the former. The oolitic or pseudo-oolitic facies includes oolites, pellets and pisolites. Organic debris are generally restricted to crinoids, foraminifera, ostracodes and gastropods. The oolites of this facies appear to grade from coarse to fine going from east to west (Kent, 1971). Evaporites are nodular and banded anhydrite, halite, penecontemporaneous dolomite, and coarse and fine red clastic rock. The latter beds predominate toward the top of the sequence. Thus, like the Devonian, the closing stage of Mississippian sedimentation is marked by clastic deposits, which probably reflect gradual emergence of the region. An unconformity, representative of uplift of the Precambrian Shield to the north, terminates the Paleozoic succession.

The Mesozoic

Jura-Triassic

Terrestrial red argillaceous quartzose sandstone, and quartzose sandy and anhydritic mudstone, succeeded by marine red beds of anhydrite and dolomite and white dolomitic limestone, lap onto the erosional surface concentrically from the Williston Basin of North Dakota. Because the Watrous Formation and the Lower Member of the Gravelbourg Formation, representative of these deposits, blanket a karstic-trellis topography, the local thickness of this group ranges from less than 30 m on the cuestas to more than 180 m in the valleys and sinks. The red beds are generally well indurated and anhydrite plugged. Thus they form an effective seal to a number of the major unconformity-capped oil reservoirs in the underlying Mississippian strata. However, local departures from impermeability, especially in relation to microfaulting, have formed sites for upward oil migration into the Watrous, Gravelbourg, Shaunavon and Mannville Formations. These are amplified by sandy and oolitic permeable sandstone in the Middle Jurassic of the southeast.

Jurassic Grey Beds

The dominantly medium green-grey to dark grey fossiliferous marine shales which make up the Upper Gravelbourg, Shaunavon and Vanguard Formations thicken to more than 270 m in south-central Saskatchewan from their eroded margin updip. The grey beds represent the continuation of the red-bed transgressive sequence and thus overlap the latter in the extreme southwest. However, their erosional subcrop lies basinward of the older deposits. Several thin but economically important tongues break the lithologic homogeneity: a) the Lower and b) Upper members of the Shaunavon Formation, and c) the Roseray Formation of the Vanguard Group.

The 10 to 30 m thick Lower member of the Shaunavon Formation is characterized by cream-coloured lithographic limestone, marked by an upper 6 m of oolite in the west and a basal introduction of dark grey shale beds eastward. Towards Manitoba, the limestone yields to dark grey shale and medium grey, fine, muscovite-rich quartzose sandstone. The Upper member comprises 10 to 22 m of lenticular quartzose sandstone, oolite, bioclastic arenite and rudite, dolomite and shale, representing mappable tidal-channel fills, supra- and infratidal shoal deposits, shell banks and beaches. The member as described lies between longitudes 108° and 109°W. These lithologies yield westward to permeable, calcareous sandstones, and eastward to shales.

The Roseray Formation is composed of well-sorted, fine-grained, weakly cemented and very permeable sand with an argillaceous matrix, and argillaceous interbeds

making up less than 10 percent of the succession in the north and about 40 percent in the south. White kaolin yields southward to dark grey glauconitic shale. The formation is 15 to 46 m thick over an area of 26,000 km^2 and projects southward from the sub-Cretaceous unconformity as a broad tongue between longitudes 108° and 104°W, to taper across the United States border as thin, lenticular argillaceous sandstones.

Like the Mississippian but unlike the Devonian, the Jurassic isopachytes (Figure 15) are restricted to the southern third of the province and are concentric on the structural Williston Basin. This concentricity reflects a post-Appalachian orogenic control exercised by the basin versus the more northwesterly shelf-like interbasin distribution of Devonian deposits.

The Cretaceous

The sandstones and shales of the Mannville Group drape southerly dipping strata, that range in age from Upper Jurassic in the extreme south to as old as Cambrian along the northern edge of the Phanerozoic. These deposits inlay a topography that was highest in the southwest of Saskatchewan and from where valleys radiated to the north, northeast and east across Jurassic and Mississippian strata, and turned north and northwest in eastern and central Saskatchewan across the Devonian. Consequently, thickness of the group ranges from less than 30 m to more than 100 m locally and 240 m regionally.

Sediments are variably kaolinitic, chloritic and illitic argillaceous, cross-bedded sandstone, ranging from white and olive green to dark grey in colour, and dark and medium grey sandy mudstone with carbonaceous and coaly beds. Marine indicators are conspicuous in the central part of the province and at certain horizons in the extreme south where fluviatile elements are otherwise dominant.

The Colorado Group (Albian-Coniacian age) consists of predominantly massive black shales with subordinate sandstone bodies tonguing into Saskatchewan from the Rocky Mountain foreland in the west and the Precambrian Shield in the north and east. A division into upper and lower subgroups is made at the base of the widespread Second White (lower) Speckled Shale (Turonian) in the west and the coeval Favel Formation in the east. The base of the Fish Scale marker, some 18 to 30 m below the top of the group, is taken as the boundary between the Upper and Lower Cretaceous. As a whole, the Colorado Group thickens fairly uniformly from the eastern edge to 500 m in the southwest corner of the province.

Shales are dominant in total thickness, but the group is stratigraphically delineated by sandstone and calcareous units. Thus, the Viking Formation of burrowed, poorly sorted and pebbly sandstone separates the black shale of the basal Joli Fou Formation from that of the Big River Formation. The Viking thins from a thickness of 54 m in the southwest to 12 m towards the north and shales out eastward. Subordinate sandstones in the Joli Fou (Spinney Hill) and in the Big River (St. Walburg) tongue in from the north. Calcareous shaly units serve to vertically delimit the Upper Colorado subgroup. Thus, progressing upward in southeastern Saskatchewan, the calcareous Favel (Turonian) is overlain by the noncalcareous Morden (Turonian-Coniacian), which in turn is succeeded by the calcareous Boyne. Although sandstone is a minor component of the Colorado, those in the southwest, such as the Medicine Hat, host the largest of the natural gas fields in Saskatchewan.

The Montana Group (Santonian to Maastrichtian) also thickens to the southwest, like the subjacent Colorado, but more so, to some 380 m (Figure 17). Dark grey to black shale, 24 m thick, of the Pembina Member of the Vermilion River Formation and the 370 m thick superjacent grey-green bentonitic and grey siliceous shale of the Riding Mountain Formation constitute the marine succession in the east. Farther west, interdigitating sandstones and siltstones separate the shale into the Lea Park, Judith River and Bearpaw Formations (oldest to youngest).

The Lea Park Formation interdigitates with grey, fine- to medium-grained sandstones and intercalated siltstones, and dark grey silty shales of the fluviomarine and continental Milk River Formation. This latter is transgressively overlapped by the Pakowki Formation, and offlapped by the mixed fluviomarine and continental Foremost-Oldman sequence of sandstones and siltstones. Likewise the Bearpaw shales intertongue with the continental Oldman Formation and the mixed fluviomarine and continental Eastend Formation. The last-mentioned unit, less than 30 m thick, is succeeded by up to 22 m

Figure 17 - Isopach Map of the Upper Cretaceous strata of Saskatchewan and Manitoba.

of white to light grey shale, siltstone and sandstone (Whitemud Formation) and 7.5 m of dark grey bentonitic shale (Battle Formation), followed disconformably by 60 m of medium-grained sandstone, bentonitic shale and muddy siltstone (Frenchman Formation), all of which are predominantly continental in origin.

The Cenozoic

In southern Saskatchewan, light grey sandstones, siltstones and silty mudstones with interbedded coal characterize the 160 to 240 m thick Ravenscrag Formation (Paleocene), which rests conformably on the Frenchman Formation in the Cypress Hills and Wood Mountain - Missouri Coteau areas. The Ravenscrag is unconformably overlain by over 170 m of conglomerate and interbedded sandstone of the Cypress Hills Formation (Oligocene). Locally, Upper Eocene conglomerate and sandstone (Swift Current Formation), and Miocene sand and gravel (Wood Mountain) up to 15 m thick cap the Ravenscrag Formation.

Mineral Industry

Metallic Minerals

The province presently produces only two metals: uranium and gold, although up to as recently as 1989, copper, zinc, silver, gold and cadmium were being mined by Hudson Bay Mining and Smelting Ltd. in their now depleted Flin Flon ore body. Historically the province has seen other significant copper and copper-zinc mines and there has also been a small amount of lead, nickel, selenium, tellurium, platinum and palladium production. The values of metallic mineral sales between 1932 and 1990 are illustrated in Figure 18. The figure shows that since 1975 when the first of the Athabasca Basin uranium mines began production, this commodity has dominated sales. Also apparent is the fall in base metal sales since the mid-eighties, reflecting the depletion of the Flin Flon ore body mined since 1930, and the rise in precious metal sales after 1985 as a result of the start up of gold mines north of La Ronge.

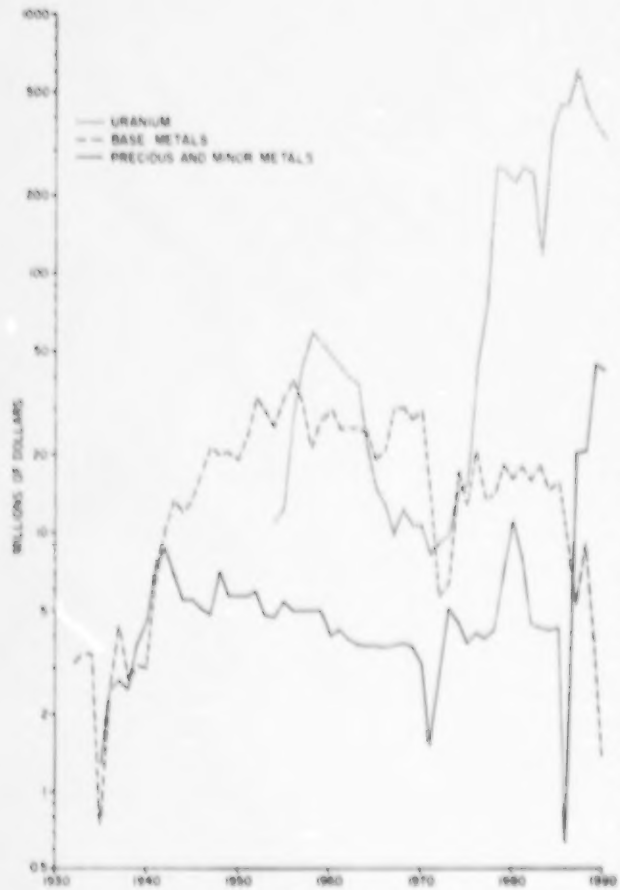


Figure 18 - Value of metallic mineral sales, 1932-1990.

Uranium

Uranium production in the province has been from two main areas and geological environments: the Beaverlodge District and the Athabasca Basin. Production from the former occurred between 1953 and 1982 and began in the latter in 1975, at the Rabbit Lake deposit, which is now mined out (Figure 19).

Beaverlodge District

The Beaverlodge deposits are characterized by epigenetic pitchblende veins and disseminations, primarily in rocks of the "Hudsonian" metamorphic basement. Some veins are present in the unconformably overlying "post-Hudsonian" red beds of the Martin Group, formed of unmetamorphosed coarse, immature clastics interbedded with alkali basalts. There appears to be a general spatial association between the outcrop of the Martin Group and the major deposits, although there is no unequivocal explanation of this relationship. Pitchblende is the chief ore mineral and thorium and rare earths are absent. Ore grades did not exceed 0.4 percent U and were commonly less than 0.2 percent U.

The epigenetic deposits have been divided into two groups showing simple and complex mineralogy. In the former, which is the more common and exemplified by Eldorado's Ace-Fay-Verna ore zones, pitchblende is accompanied by coffinite, brannerite, nolanite, pyrite, chalcopyrite and galena. In the latter, illustrated by the Nicholson ore zones, pitchblende occurs with coffinite, thucolite, sulphides, arsenides and selenides of nickel, cobalt, copper, lead and zinc, native gold and silver, and platinum group metals.

The complex deposits are mineralogically similar to those of the Athabasca Basin, and there is some evidence to suggest that they are also of similar age. In this eventuality, they would be geologically 350 to 650 Ma younger than the ca. 1750 Ma deposits of simple mineralogy with which they are spatially associated.

The early generation of epigenetic pitchblende in veins and as disseminations exhibits a strong structural control, occurring in the fractured wall rocks of major faults. Accordingly, deposits are often tabular and of large vertical and horizontal extent. Red hematitic alteration of wall rocks accompanied by albitization and development of chlorite and calcite is typical adjacent to early pitchblende veins, although it is of variable intensity.

Production from the Beaverlodge district from 1953 to 1982 is summarized in Table 7 and the locations of the major producers are shown in Figure 20. Output of the Eldorado Ace-Fay-Verna operation and the Gunnar Mine clearly eclipsed that of the other producers.

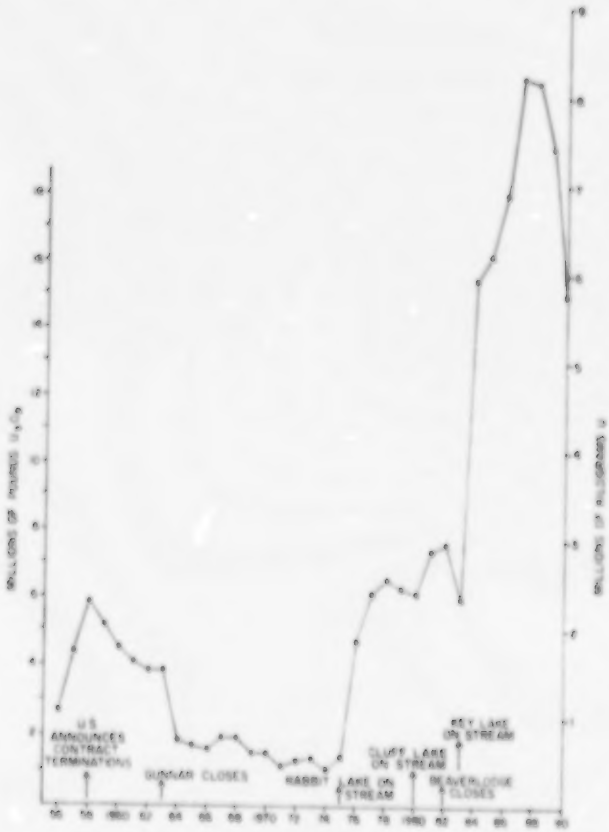


Figure 19 - Uranium production, 1956-1990.

Ace-Fay-Verna Mine (Plate 4)

Eldorado began production in 1953 at some 450 t/day and by 1958, with enlargement of the plant reached 1800 t/day. Maximum throughput achieved was 2100 t/day during the peak production period, between 1958 and 1968, when annual yields ranged from 655 000 to 965 000 kg U. The subsequent general decline in output was never significantly reversed, even though an expansion program was initiated in 1975. When the mine closed in 1982, output was around 385 000 kg U annually.

The average grade of ore mineral was about 0.17 percent U through the peak production period and in excess of 0.25 percent U through a period of selective mining in the early seventies. Mining was underground, utilizing three surface shafts and two internal winzes, and was carried out on 33 levels to a depth of around 1675 m. The mill, unlike most uranium mills in Saskatchewan, utilized a complex, energy intensive carbonate leach as the main process; however, since the ore contained pyrite, there was also a more conventional acid leach circuit.

The Ace-Fay-Verna deposit occurs as sporadic zones of mineralization over a distance of 5 km adjacent to the St. Louis Fault, which strikes east-northeasterly and dips at 50° to the south. The fault separates meta-argillite, chlorite-epidote rock and red altered feldspar rock in the footwall from alaskite granite and paragneiss overlain unconformably by the downfaulted Martin Group in the hanging wall.

The Ace-Fay zones are located in the footwall. Breccia type ore zones occur within 15 m of the fault and are made up of a matrix of pitchblende, quartz, calcite, chlorite and pyrite in feldspar rock and quartz. Vein-type ore zones are associated with fractures striking roughly parallel to the fault and form single or anastomosing bundles that include pitchblende, quartz, calcite, chlorite, pyrite and, locally, clausthalite and nolanite. The Ura ore zones in the hanging wall are present in flat-lying shears above and below the unconformity separating the Martin Group from the underlying basement alaskite. Other ore zones occur in alaskite and paragneiss in breccia and shears. Wall rocks are impregnated and veined by hematite, epidote and quartz, especially in footwall meta-argillites.

The Verna zones occur in a wedge-shaped mass of meta-argillite, hornblende schist and quartzite enclosed by alaskite granite in the hanging wall of the St. Louis Fault. Veins and stockworks of pitchblende include pink calcite and pyrite. White calcite and quartz occur in barren and low-grade sections. Alteration is similar to that observed in the Ace-Fay deposit. The zones are tabular to lensoid and up to 25 m in width and 250 m in length.

Gunnar Mine (Plate 5)

The radioactive boulders leading to the Gunnar deposit were discovered in 1952. The pipelike orebody, plunging at 45° to the south-southeast, around 150 m in diameter and 300 m deep, was outlined by some 22 500 m of diamond drilling on a 22.5

Table 7 - Major Uranium Producers, Beaverlodge District

	Uranium Mine	*Production (t U)*
1.	Eldorado, Ace-Fay-Verna (1A)	16 035
2.	Gunnar	8 892
3.	Eldorado, Hab	783
4.	Rix Smitty	436
5.	Cinch Lake	285
6.	Cayzor Athabaska	187
7.	Eldorado, Dubyna	163
8.	Lorado	89
9.	Eldorado, Eagle	85
10.	Rix Leonard	77
11.	Nicholson	41
12.	National Exploration	30
13.	Nesbitt Labine	23
14.	Eldorado, Fish Hook	15
15.	Eldorado, Martin Lake	11
16.	Uranium Ridge	10
		25 142

Figure 20 - Major uranium producers of the Beaverlodge District in relation to outcrop of the Martin and Athabasca Groups. Numbers refer to Table 7.

m square grid pattern. The orebody was estimated to contain around 3.6 million tonnes of ore grading 0.17 percent U. Production commenced in September 1955 and continued until the orebody became depleted in Octo-ber 1963. Extraction was initially from open pit until 1958, from underground and open pit until October 1961, and thence solely from underground. Some 5.0 million tonnes of ore grading 0.148 percent U were milled.

The Gunnar deposit is hosted by a coarse-grained microcline-albite granite, the Gunnar granite, which is in contact with banded amphibolitic and quartzitic gneisses to the north. The granite comprises about 65 percent albite, 25 percent quartz, generally less than 5 percent potassium feldspar and minor chlorite (after biotite) and muscovite. Within the granite, adjacent to the sedimentary gneiss contact, bodies of syenite formed by albitization of Gunnar granite are present. Individual bodies are up to 500 m long and 125 m wide. Calcite has locally replaced quartz, yielding a calcite syenite, similar to episyenites of the Massif Central of France. This rock, when leached, appears as a vuggy 'sponge rock'.

The orebody occurs in brecciated portions of the syenite. Pitchblende, together with small amounts of uranophane, rims albite and forms stringers, blebs and disseminated grains in the host rock. Gangue minerals are calcite, euhedral quartz, hematite, chlorite, kaolinite, pyrite, chalcopyrite, and galena.

Plate 4 - Fay headframe and mill, Beaverlodge, 1959 (courtesy of Saskatchewan Archives Board, Photo No. 59-322-36).

Plate 5 - Gunnar open pit and mill, 1956 (courtesy of Saskatchewan Archives Board, Photo No. 56-305-62).

Athabasca Basin

The uranium deposits of the Athabasca Basin are often referred to as unconformity-type, because of their spatial association with the sub-Athabasca Group unconformity. The Athabasca Group itself is an unmetamorphosed fluvial and marine clastic sequence dominated by quartz sandstones and deposited in Paleohelikian times (ca. 1400-1700 Ma). The Group covers an area of approximately 100 000 km^2 and is up to 1400 m thick.

The Basin is host to the richest uranium deposits in the world (Figure 21). Reserves are estimated at about 350 000 t of U metal in the lower cost categories (up to $150/kg U) representing some 10 percent of the reasonably assured low cost uranium reserves of the western world and approximately 75 percent of Canadian reserves. Most of the Athabasca Basin reserves are contained within three major deposits at Key Lake, Cigar Lake and P2 north (Table 8).

Discovery costs (in 1985 dollars) per kg U metal between 1971 and 1983 have been estimated at $1.53 in Saskatchewan compared with $13.58 in the remainder of Canada. A total of 383 800 t of U metal is identified as having been found during this period for an expenditure of $588 million.

Development of existing and new production facilities has kept apace of the new discoveries. Current uranium production peaked in 1987 and 1988 at around 8.2 million kg U, making Saskatchewan the western world's leading uranium producer with 66 percent of Canadian production and 22 percent of the western world's production.

The main geological characteristics of these deposits are well defined. The highest grade ore straddles the unconformity, although mineralization may extend a few hundred metres above and below it. There is a definite association with graphitic rocks in the underlying metamorphic basement and many ore zones occur adjacent to faults, which displace the sub-Athabasca contact by several tens of metres. Both reverse faults and normal faults appear to have been influential in genesis of the deposits.

The unconformity deposits are of extremely high grade and marked by a complex mineralogy and geochemistry. Intersections of several tens of percent uranium are common. Pechblende and coffinite, the primary uranium minerals, are accompanied by pararammelsbergite, rammelsbergite, niccolite, gersdorffite, millerite, carrollite, molybdenite, various copper sulphides, clausthalite, galena, sphalerite, hematite, goethite, psilomelane, copper, gold, selenium and others. Gangue minerals include quartz, calcite, dolomite, ankerite, siderite, chlorite, sericite and adularia. Geochemically, uranium is accompanied by Ni, Co, Mo, Cu, Pb, Zn, Mn, Fe, V, Ag, Au, Pt-group elements, S, Se and As. In some deposits, the diversity of minerals and concentration of elements associated with uranium is small, whereas in others many different mineral phases are present and elements are associated with uranium in potentially if not economically mineable quantities (eg. gold at Cluff Lake, nickel at Key Lake).

Deposits are surrounded by extensive alteration envelopes penetrating both the Athabasca Group and crystalline basement. This alteration is distinct from that of the lateritic weathering profile in the uppermost basement, and is variously marked by chloritization, tourmalinization, hematization (several episodes), illitization, silicification and dolomitization. Other features include the destruction of graphite, corrosion of quartz and formation of residual clay seams and caps above mineralization in the Athabasca Group, bleaching (removal of hematite) and euhedral quartz ± siderite ± pyrite ± hematite-filled fractures. Age dating indicates that the deposits were first emplaced around 1400 Ma ago (i.e. from 50 to 300 Ma after deposition of the Athabasca Group).

Rabbit Lake Mine

Rabbit Lake, on the eastern margin of the Athabasca Basin, was the first of the new unconformity-type uranium deposits to be brought into production. Initially owned by Gulf Minerals (Canada) Ltd. and Uranerz (Canada) Ltd., the deposit and surrounding mineral

Table 8 - Major Athabasca Basin Unconformity-Type Uranium Deposits

	Deposit	Ownership	Discovery date	Reserves tonnes U	Grade % U	Athabasca Gp. thickness (m)	Basement Rock Types	Depth of Mineralization (m)	Remarks
1	Rabbit Lake	Cameco - Uranerz Exploration and Mining Ltd.	1968	15 769*	0.27	Absent (eroded)	Meta-arkose, plagioclasite (in part graphitic), calcsilicate dolomitic marble, granite segregation pegmatite, microgranite	0-200	In hanging wall of Rabbit Lake thrust fault. Subcrop below drift. Mineralized boulder train. Mined out.
2A	Collins Bay A	"	1971	6 500	4.83	Absent (eroded)	Pelitic graphitic gneiss, granite segregation pegmatite in contact with granitoid gneiss	5-20	In clay zone at Athabasca Group unconformity in hanging wall of Collins Bay thrust fault. Subcrop below drift. Mineralized boulder train.
2B	Collins Bay B	"	1977	15 750**	0.61	25	Pelitic graphitic gneiss, granite segregation pegmatite in contact with granitoid gneiss	5-30	Dominantly in Athabasca Group in footwall of Collins Bay thrust fault. Subcrop below drift
2C	Collins Bay D	"	1979	2 150	1.66	-	Pelitic graphitic gneiss, granite segregation pegmatite	-	Adjacent to Collins Bay thrust fault
3	Raven	"	1972	3 650	0.12	Absent (eroded)	Sillimanite quartzite, calcareous meta-arkose, semipelitic gneiss	0-300	Fracture controlled mineralization in altered basement
3A	Horseshoe	"	1974	1 550	0.14	Absent (eroded)	Sillimanite quartzite	60-300	Fracture controlled mineralization in altered basement
4A	Eagle Point South Zone	"	1980	28 850	1.39	Absent (eroded)	Pelitic-semipelitic gneiss (in part graphitic), quartzite, granite segregation pegmatite	0-460	In hanging wall of Collins Bay thrust fault. Structurally controlled in altered basement. Concordant lenses subcrop below drift
4B	Eagle Point North Zone	"	1980	22 300	1.76	Absent (eroded)	"	0-300	In hanging wall of Collins Bay fault. Structurally controlled in altered basement. Discordant lenses.
5	Fond-du-Lac	Cameco	1967	400	0.2	30	Meta-arkose, pelitic gneiss (occasionally graphitic)	10-30	Mineralization in Athabasca Group. Subcrop below drift. Mineralized boulder train
6	West Bear	Cameco	1977	450	0.37	-	Pelitic graphitic gneiss	17-40	Mineralization occurs at unconformity
7	Midwest	Denison Mines Ltd. - Uranerz Exploration and Mining Ltd. - PNC - Bow Valley Industries Ltd.	1978	13 600	3.8	200	Pelitic graphitic gneiss locally with garnet, granite segregation pegmatite, bounded by granitoid gneiss; crosscutting diabase dykes	0-300	Dominantly at sub-Athabasca Group unconformity, mineralization extends more than 100 m below unconformity and to surface (source of mineralized boulder train)

8	Dawn Lake (11, 11A, 11B and 14 zones)	Cameco - Cogema (Canada) Ltd. - PNC - CEGB - Kepco	1978	11 500	1.7	100	Pelitic graphitic gneiss, calc-silicate, granite segregation pegmatite	30-200	Mineralization extends 50m above and 100m below the Sub-Athabasca Group unconformity. No surface expression.
9A	McClean Lake (North and South Zones)	Minatco Ltd.	North 1979 South 1980	5 500	1.5	150	Pelitic graphitic gneiss granite segregation pegmatite	115-190	Mineralization extends above and below sub-Athabasca Group unconformity. No surface expression.
9B	Sue Zones	"	1988	-	-	-	-	-	-
10	Jeb	"	1982	1 800	-	100	Pelitic graphitic gneiss	85-120	No surface expression
11	Key Lake	Cameco - Uranerz Exploration and Mining Limited	1975	73 900**	2.0	0-60	Graphitic pelitic gneiss adjacent to granitiod gneiss massif	50-150	Mineralization extends above and below sub-Athabasca Group unconformity but predominantly below within 20m of unconformity. Subcrop below drift. Mineralized fluvioglacial boulder train
12	Cigar Lake	Cameco - Cogema (Canada) Ltd. - Idemitsu Uranium Exploration Canada Ltd. - Corona Grande - Kepco	1981	110 000 (38 500 additional estimated)	12.3 (4)	410-450	Graphitic pelitic gneiss, minor calc-silicate, granite segregation pegmatite	± 440	Mineralization predominantly in lens at sub-Athabasca Group unconformity. Some fracture controlled mineralization above and below unconformity No surface expression
13	Maurice Bay	Cameco - Uranerz Exploration and Mining Ltd.	1977	600	0.5	0-130	Pelitic gneiss (in part graphitic), minor quartzite and amphibolite	0-150	Mineralization in three zones. Athabasca Group (B and Main) and basement (A). Subcrop below drift. Mineralized boulder train
14A	Cluff Lake D	Amok Ltd. - Cameco	1969	4 170*	6.0	-	Pelitic to semipelitic gneiss (in part graphitic) (Peter River Gneiss)	0-35	Mineralization in Athabasca Group sandstones and siltstones at thrust fault-inverted unconformity. Mineralized boulder train. Subcrop below drift. Mined out.
14B	Cluff Lake (other)	"	1969-1980	18 850***	0.63	-	Pelitic to semipelitic gneiss (in part graphitic (Peter River Gneiss) quartzofeldspathic gneiss (Earl River Gneiss), granite pegmatite	0-300	Fracture controlled mineralization in altered basement
15	P2 North	Cameco - Agip Resources Ltd. - Cogema (Canada) Ltd. - Uranerz Exploration and Mining Ltd. - Interuranium Canada Ltd.	1989	77 000****	3.4	460-590	Pelitic graphic gneiss-quartzite	± 550	Mineralization in Athabasca Group underlying overthrust basement wedge

* Actual production, now mined out
** Original resources, now depleted by production
*** 1988 reserves (original reserves - production + discoveries)
**** Preliminary estimate

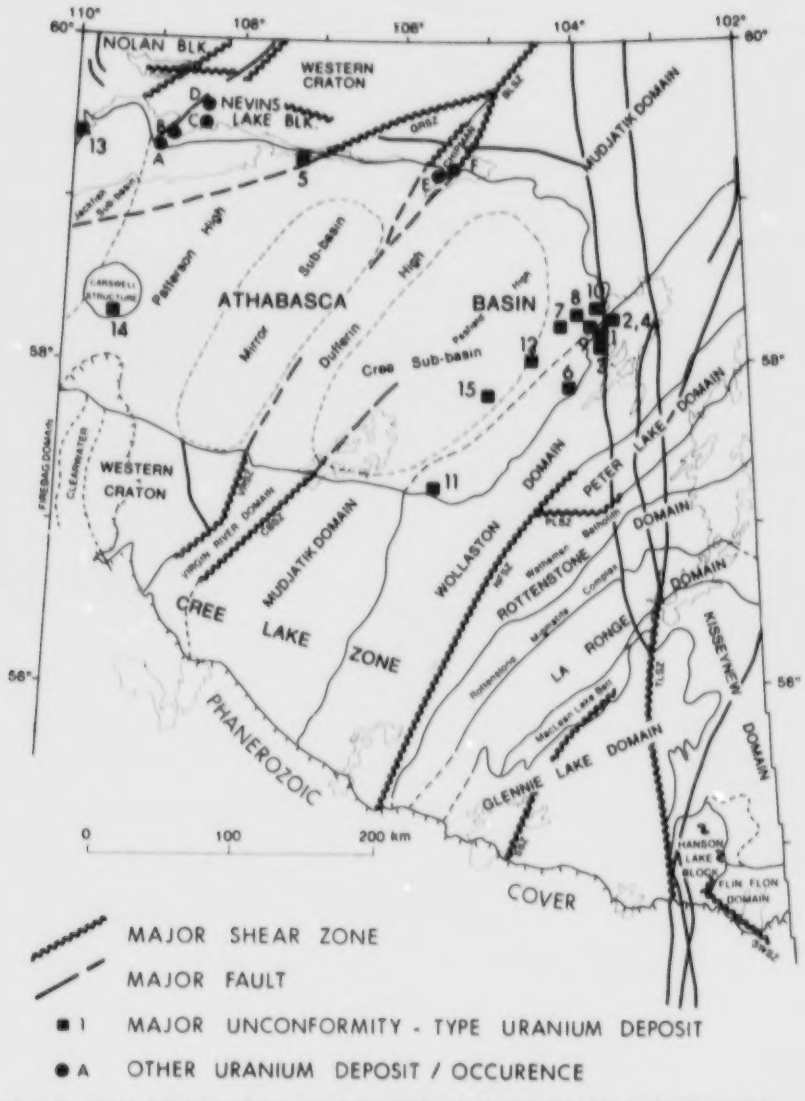


Figure 21 - Major Athabasca Basin 'unconformity-type' uranium deposits and tectonic subdivisions of the Saskatchewan Shield. Numbers refer to Table 8. Major shear zones: VRSZ-BLSZ, Virgin River - Black Lake; NFSZ - PLSZ, Needle Falls-Parker Lake; SSZ; Stanley; SWSZ, Sturgeon Weir; TLSZ, Tabbernor Lake; CBSZ, Cable Bay.

properties were acquired by Eldorado Resources Ltd. in 1982. Present ownership is by Cameco (66 2/3%) and Uranerz Exploration and Mining Ltd. (33 1/3%). It was discovered in 1968, during ground follow-up to an airborne radiometric survey which detected a uranium anomaly resulting from radioactive glacial overburden. Subsequent work showed the deposit to be associated with a conductivity anomaly, low magnetic and gravity signatures, and lake bottom sediment geochemical highs.

Stripping began in 1974 following a development drilling program and the mill started up in 1975. Peak annual production reached 2056 t U from ore grading around 0.4 percent U. Mining was completed in 1984 and the pit was turned into a depository for mill tailings from the remaining stockpiled Rabbit Lake ore and new Collins Bay B zone ore. Total production from Rabbit Lake was 15 769 t U from ore grading an average of 0.27 percent U and initially estimated reserves of 17 300 t U.

The deposit is hosted by Lower Proterozoic metamorphic rocks of the sub-Athabasca basement, comprising interlayered meta-arkoses and calc-silicates in the hanging wall (upper gneisses), massive meta-arkose in the core of the ore zone and plagioclasite (in part graphitic), calc-silicates and dolomitic marbles in the footwall. The hanging wall gneisses are cut by subconcordant sheets of pink granite/granite pegmatite. The Rabbit Lake thrust fault, which underlies the deposit, dips 30° to the south-southeast and downthrows the Athabasca Group sandstones to the northwest at least 75 m, to lie against the crystalline basement. An older northeasterly-trending, steeply dipping fault bounds the ore zone to the southeast.

The ore zone was elongated in a northeasterly direction and had the shape of a laterally flattened pipe, around 550 m long, up to 250 m wide and 200 m deep tilted to the northwest. A high-grade core is surrounded by a lower grade envelope of mineralization. Host rock alteration pervades and surrounds the orebody and is typified by Mg-chloritization, dolomitization, silicification, tourmalinization and hematization. Mineralization is made up of several different generations of pitchblende and coffinite, accompanied by a broad suite of minerals including euhedral quartz and dolomite, calcite, siderite, hematite, chlorite, adularia, sulphides, native copper and carbon buttons. Secondary uranium minerals, uranium mineral coatings and impregnations are also developed. On a large scale mineralization is geochemically simple, comprising essentially uranium with only minor con-

centrations of Ni, As, Co, Se etc., which characterize many other unconformity type deposits.

Collins Bay B Zone Mine

The Collins Bay deposits are situated some 10 km northeast of Rabbit Lake. Three principal zones have been recognized, the A, B and D, along a 3 km mineralized trend. The A zone was found in 1971 as a result of ground checking of airborne electromagnetic anomalies. A mineralized boulder train was discovered by prospectors and traced to source in Collins Bay. Drilling revealed high-grade uranium-nickel mineralization. In 1976, following the recognition of possible ore controls at Key Lake, the A zone was re-evaluated and the strike extension of the underlying electromagnetic trend further explored. Drilling led in 1977 to the B zone, some 2 km south of the A, and in 1979 to the D zone, situated between the A and B zones. Reserves are estimated at 6500 t U grading 4.83 percent U in the A zone, l5 769 t U grading 0.61 percent U in the B zone and 2154 t U grading 1.66 percent U in the D zone. The B zone has recently been completed by owners Cameco (66 2/3%) and Uranerz Exploration and Mining Ltd. (33 1/3%) by open pit and a significant proportion of reserves stockpiled. Site production capacity, not yet fully utilized, is some 4600 t U per year. The A and D zones will also be mined by open pit and phased into production when needed.

The Collins Bay area is underlain by Lower Proterozoic metasediments, granitoid gneisses of probable Archean age and sandstones of the Athabasca Group. The granitoid gneisses are overlain by the Athabasca Group, downthrown by the northeasterly-trending Collins Bay (thrust) Fault.

The B zone is approximately 915 m long, 30-122 m wide and 30 m in average thickness. It is confined for the most part to the footwall of the Collins Bay thrust, primarily within sandstones and conglomerates of the Athabasca Group, which unconformably overlie Archean granitoids. Some mineralization occurs in the hanging wall, formed by upthrown graphitic metasediments. The orebody comprises a lens or group of lenses parallel to the strike of the thrust, which is northerly except at the north end of the orebody, where it turns into the regional northeasterly trend. Imbrication characterizes the northerly-trending segment of the fault.

Ore and associated minerals include pitchblende, coffinite, niccolite, rammelsbergite, gersdorffite, maucherite, bravoite, violarite, chalcopyrite and other copper sulphides. Pyrite, covellite, bornite, tennantite, millerite, polydimite and safflorite are present locally. Unlike the Rabbit Lake deposit, the Collins Bay B zone is geochemically complex and contains significant nickel and arsenic in association with uranium.

Cluff Lake Mine (Plates 6 and 7)

The Cluff Lake deposits, owned jointly by Amok (Canada) Ltd. (80%) and Cameco (20%) occur at or near the southern edge of an uplifted basement core within the western part of the Athabasca Basin. Uranium

Plate 7 - Selective mining in the Claude ore body at Cluff Lake.

mineralization was first discovered in 1968 as a result of follow-up work to an airborne radiometric survey which had revealed several weak anomalies in the area. To date, several significant zones of mineralization, the D, N, OP, Dominique-Peter, Dominique-Janine, South Dominique-Janine and Claude, and numerous showings have been found. The zones outcrop or subcrop below glacial drift and give rise to geochemical dispersion haloes in the drift, which are detectable by ground and, in some cases, airborne prospecting.

The Cluff Lake deposits have been estimated to contain in excess of 20 million kg U, the grade of the ore varying substantially in different deposits. The D zone, for example, had an average grade of 3.41 percent U, whereas the others grade around 0.5 percent U. Mining of the deposits has been in two stages, commencing with the high-grade D zone, and now continuing with the lower grade zones. At present, production is from the Dominique-Janine open pit and from the Dominique-Peter underground mine. Phase I open pit mining and milling of the D deposit began in May 1980 and continued to 1983. Uranium bearing gravimetric tails from this phase were processed between May 1983 and August 1984. Also in 1983 Phase II operations were initiated with the mining of the Claude deposit by open pit and of the OP deposit underground. Depletion of the OP orebody was followed by development of the Dominique-Peter orebody, also underground, and in 1989 of the Claude orebody by development of the

Dominique-Janine (north) open pit. Gold residually concentrated in the leach tailings derived from Phase I processing of D zone ore gravimetric concentrate was extracted in 1987-88. Production was 8090 troy ounces.

The basement core of the circular Carswell Structure, which may be of meteorite impact origin, is surrounded by successive, 4 to 5 km wide rings of deformed and fragmented Athabasca Group sandstones and stromatolitic dolomite. The basement rocks principally comprise granitoid gneisses (Earl River complex) and metasedimentary gneisses (Peter River gneisses) invaded by sheets of pink leucocratic garnetiferous granite/granite pegmatite.

The D zone was located in an overthrust block at the inverted sub-Athabasca Group unconformity, which dips moderately northwards. Graphitic Peter River gneisses overlie interbedded siltstones, conglomerates and sandstones of the Athabasca Group. Massive ore occurred for the greater part in the siltstones, and in the superjacent basement in proximity to a mylonite. The orebody was mined by openpit in 1980 and 1981, yielding 4370 t of uranium at a grade of 3.41 percent U. It was ellipsoidal, about 140 m long, up to 25 m wide and 7 m thick, with mineralization forming discontinuous lenses. Pitchblende, uraninite and coffinite ore minerals were associated with gold and gold tellurides, native selenium and lead, bismuth, nickel and cobalt arsenides, jordisite, pyrite, galena and chalcopyrite. Hydrocarbon buttons and other carbonaceous material also occurred in the ore. Ore emplacement was accompanied by pervasive hydrothermal alteration, affecting both basement and the Athabasca Group.

The Claude deposit, now depleted, occurred within Peter River gneisses, which are in part graphitic in character and interlayered with granitoids. For the most part, mineralization was localized within an easterly-trending subvertical shear zone containing rotated fault blocks, although northeasterly-trending faults were also mineralized. The deposit was around 600 m long, 200 m wide and had a maximum depth of 90 m.

A decline was put down in 1979 and an experimental pit was opened in 1982. Mining by open pit took place between 1983 and 1989. Calculated tonnage for this orebody is given as 2097 t of U metal at a grade of 0.36 percent U.

Mineralization comprises uraninite and coffinite in association with minor clausthalite, galena, pyrite, chalcopyrite, sphalerite, jordisite, covellite and hydrocarbon buttons. Alteration, distinguished by hematization and chloritization/argillization, is intimately associated with the mineralization, which is typically developed at the redox interface marked by hematized and pale green, bleached rock.

The OP deposit comprises fracture controlled mineralization in two settings. The OP mineralization occurs at the intersection of two thrust faults which superimpose fresh Peter River gneisses over Athabasca Group, the palaeoweathered basement (regolith), and other basement gneisses. The faults dip gently to the north and north-northwest respectively. Further east mineralization is present discontinuously in subvertical northerly-trending fractures with vein quartz, which cut Peter River gneisses. It comprises uraninite with chalcopyrite, galena, clausthalite, and pyrite, all deposited on quartz crystals. Coffinite and Mg chlorite have been observed with mineralization, alteration zones around the veins are very narrow. The deposit was explored by decline in 1980 and 1981 and mined underground between 1983 and 1985. Some high-cost resources remain in the deposit.

The Dominique-Peter orebody was contained entirely within the basement in proximity to a mylonite zone marking the contact of the Peter River and Earl River gneisses. These gneisses are cut by three sets of faults, all of which displace the mylonite zone. Mineralization occurs as fracture fillings, veinlets and disseminations usually within tens of metres of the mylonite zone, mainly in the northerly and east-northeasterly faults cutting Peter River gneisses and mylonite. Two mineralization assemblages have been observed: a uraninite-polymetallic sulphide assemblage and a uraninite-dravite-simple sulphide assemblage. As of December 31, 1984 the Dominique-Peter orebody has been estimated to contain 11 587 t of U metal in ores grading 0.66 percent U.

The geological environment of the Dominique-Janine deposit resembles that of Dominique-Peter. The contact between the Peter River and Earl River gneisses is fault controlled and cross-cut by the subvertical northerly-trending main ore structures. Mineralization occurs within these structures where they are intersected by steeply northwesterly dipping faults. Regolith and small blocks of Athabasca Group occur in the open pit illustrating the proximity of the sub-Athabasca Group unconformity. The deposit contains reserves of 874 t of U metal in ores grading 3.8 percent U.

Key Lake Mine

The Key Lake deposits are jointly owned by Cameco (66 2/3%) and Uranerz Exploration and Mining Ltd. (33.3%). They lie on the southeastern margin of the Athabasca Basin, and were discovered in 1975 by a combination of airborne radiometrics, mineralized boulder prospecting and geophysical and geochemical surveys. The initial clue was, in fact, a uranium anomaly in lake water identified in 1969, but not further pursued. Uranerz geologists, on visiting the anomaly area in late 1971, found high-grade pitchblende boulders derived by fluvioglacial erosion from the Gaertner orebody. These boulders were traced to source and drilling eventually identified *in situ* mineralization. The orebodies are the Gaertner and Deilmann and a zone of mineralized overburden. Grade is of the order of 2 percent U, with substantial associated nickel, cobalt and arsenic. Initially estimated reserves were 73 900 t U. A small proportion of these reserves (around 8%) occurs as "cobble ore" (glacial deposits in which mineralized boulders are sufficiently concentrated to form ore grading around 0.6 percent U). Mining began in 1983 by open pit methods at an annual production rate of around 4.6 million kg U. Operation of the Gaertner pit has now been completed and

production from Deilmann pit has been ongoing since 1989.

The orebodies are underlain by Lower Proterozoic graphitic metasediments, which mantle probable Archean granite gneiss domes. Both groups of rocks are overlain unconformably by the Athabasca Group, which comprises basal conglomerates grading upwards into sandstones.

The orebodies are long and narrow. The more northerly lying Deilmann exceeds 900 m in length, varies in width from 30 to 50 m and is about 40 m deep; the Gaertner was about 800 m long and is 10 to 50 m wide and 60 m thick. The orebodies are separated by a 'gap' of approximately 1 km, where glacial erosion has penetrated below the Athabasca Group into the underlying basement. Mineralization occurs where a northeasterly-trending reverse fault showing a vertical displacement of 30 m intersects the sub-Athabasca Group unconformity. In the Gaertner deposit, the hanging wall of the fault comprises sillimanite-cordierite-graphite gneisses of the "main graphite" zone, which contain up to 30 percent graphite and 3 percent pyrite. Mineralization is hosted, as veins, massive nodules and disseminations, largely by downfaulted Athabasca Group sandstones which are extensively fractured, quartz corroded and clay altered. Some mineralization extends to a depth of 30 m into the underlying basement, formed by altered biotite gneisses which are reported to be in part mylonitized, folded and brecciated.

The Deilmann deposit is less well described by virtue of its later development. Fracture controlled ore zones in the crystalline basement thicken upwards to the unconformity where massive ore occurs. The east-northeast-trending basement fractures give rise to mineralized 'roots' extending over 100 m down dip. Some mineralization occurs in graphitic gneisses, however, ore shoots are characteristically in adjacent biotite gneisses. Perched ore bodies occur in the Athabasca Group sandstones and disjointed satellite orebodies are present at the unconformity where it is intersected by cross-faults.

The ore minerals comprise principally pitchblende and coffinite, accompanied by nickel arsenides, sulpharsenides and sulphides. Cobalt, molybdenum, lead, zinc, copper, gold and silver are present as minor constituents of the ore.

Gold

Gold production in the province has been from placer operations on the North Saskatchewan River and from gold and base metal mines in the northern Shield. Of this, approximately 90 percent has originated as a byproduct from the Hudson Bay Mining and Smelting Company's copper-zinc mine at Flin Flon (Table 9).

More than 200 gold occurrences are known and, with the exception of a few placers, all are in the Precambrian Shield. Only the Box Mine at Goldfields, and the Star Lake, Jolu and Jasper Mines in the La Ronge Gold Belt have seen significant production. Whether or not this reflects a true absence of potential or a lack of exploration is an appropriate question. In this respect, it should be noted that estimated total exploration expenditures (in 1985 dollars) between 1946 and 1990 are some $200 million in Saskatchewan, in contrast to some $2000 million in Quebec and $1750 million in Ontario. In Saskatchewan three new mines were brought into production since the start of 1987 and a fourth is presently in construction.

Table 9 - Saskatchewan Gold Production

Type/Location/Mine	*Year*	*oz.*
Placer		
North Saskatchewan River (Alberta/Saskatchewan)	1887-1902	864
North Saskatchewan River (Saskatchewan)	1938-43	274
North Saskatchewan River (Saskatchewan)	1947-49	22
Lode Gold		
Henning Maloney and others	1933-47	810[1]
Prince Albert (Monarch)	1937, 1940-42	4883
Box	1939-42	60,066
Mallard Lake (Jolu)	1973-75	555[1]
Star Lake	1986-89	76,947[2]
Jolu (Rod Zone)	1988-	(159,986)[4]
Jasper	1990-	(33,743)[4]
Rio	1984, 1988-89	n/a
Base Metal		
Flin Flon Mine[3]	1930-87	3,000,000[1]
Birch Lake	1957-60	813
Coronation	1960-64	75,055
Rottenstone	1965-68	363
Anglo-Rouyn	1966-72	67,652
Hanson Lake	1967-69	985
Flexar	1969-72	7357
Uranium		
Cluff Lake	1987-88	7826

[1]estimated
[2]includes production from 21 zone and Rush Lake zone
[3]whole deposit Saskatchewan/Manitoba
[4]production to end of 1990
n/a - not available at time of writing

Placer Production (Plate 8)

Placer gold production in the North Saskatchewan River is poorly documented. Gold has been gleaned from between Rocky Mountain House, Alberta and Prince Albert, Saskatchewan. Most mining has been small scale and involved working of river bank gravels in grizzlies and recovering the fine flour gold on blankets, although dredges were operated between 1887 and 1909. In 1904-05, for example, a steam powered dredge 30 m long, with a beam of 8.5 m and capable of working 1000 m^3 of gravel per day was assembled in Prince Albert. It worked at Crutwell, 32 km upstream from this

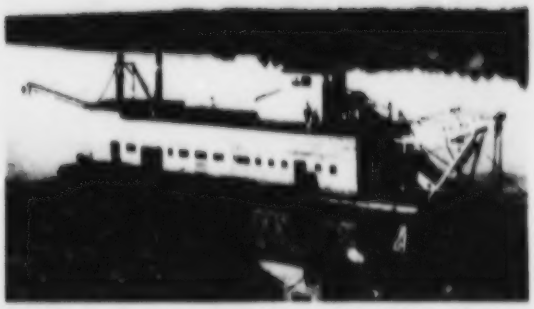


Plate 8 - Large dredge, North Saskatchewan River, 1905 (courtesy of Saskatchewan Archives Board, Photo No. R-A 5761).

town, until 1909. Two other rivers north of the Saskatchewan, the Waterhen and Poplar were examined for their placer potential, but apparently without success.

Lode Gold Deposits and Production

Gold mineralization is found particularly in the Lower Proterozoic volcanoplutonic regimes of the La Ronge and Flin Flon greenstone belts (Figure 22), in the Glennie Lake region to the east of the La Ronge belt, and in the Goldfields and Pine Channel areas north of Lake Athabasca. Gold mineralization in the La Ronge belt is mostly structurally controlled and of quartz-vein type. Host rocks while including metavolcanics and metasediments are predominantly plutons of varied composition. Controlling structures may be high-temperature shear zones essentially contemporaneous with the main thermotectonic events (Star Lake 21 zone, Rod zone, Jasper zone, Pap zone and Bakos zone and also the Seabee deposit in the Glennie Lake Domain), or later (?), low-temperature retrograde, regional fault structures such as the Byers Fault (Tower East and Weedy B-Golden Heart zones). Another style of structurally controlled mineralization is illustrated by the Komis deposit at Waddy Lake where swarms of north-south striking quartz veins intrude meta-andesites flanking a late-tectonic diapiric granodiorite-granite stock.

Stratiform gold occurrences are most extensive in the Sulphide Lake area, where gold is closely related to the presence of black, carbonaceous, sulphidic meta-argillite layers (lean iron formation) developed during hiatus in intermediate-felsic volcanism and sedimentation.

The Flin Flon-Amisk Lake area features a spectrum of pre- and syn- to late-tectonic mineralization. Early-generation gold occurrences (Monarch Mine, Graham Mine, Laurel Lake deposit) in the West Channel of Amisk Lake are quartz-vein systems surrounded by alteration haloes of carbonate, sericite and silica, developed in metavolcanics, interlayered metasediments and felsic intrusives in both subvolcanic and structural settings. Formation in a near-surface, possibly epithermal environment is suggested. By contrast, the Flin Flon area is characterized by structurally controlled deposits in metavolcanics, and invading plutons. Early quartz-sulphide-gold veins were emplaced in intermittently active fractures during orogenesis (Newcor Mine); whereas later predominantly plutonic hosted deposits (Rio, Phantom Lake Mine, Henning-Maloney Mine) were likely generated by an anorogenic porphyry system.

The Pine Channel area, north of Lake Athabasca, is typified by gold-bearing quartz veins occupying northwest-trending dilational fractures. Host rocks are retrogressed Archean, granulite-facies, garnetiferous quartzofeldspathic gneisses and hypersthene-bearing metabasic rocks (norites). Presumably, gold was derived from the country rocks by retrogressive metamorphic fluids.

At Goldfields, gold mineralization is hosted in discrete Lower Proterozoic granitic bodies cut by quartz-vein stockworks. The former Box Mine and the Athona and Frontier prospects are hosted in granites which may have been metasomatically derived by feldspathization (potassium metasomatism) of feldspathic quartzites. The quartz-vein stockworks are structurally controlled and developed during a late tectonic event which was accompanied by retrograde metamorphism marked by regional chloritization and in the Box and Athona granites by albitization.

Present exploration interest has focussed on the La Ronge belt and the Glennie Lake area to the east. The reserves identified in Saskatchewan's gold mines and significant gold prospects are summarized in Table 10.

Box Mine (Plate 9)

The Box deposit was staked in 1934 and within a year underwent development by The Consolidated Mining and Smelting Co. of Canada Ltd. (now Cominco Ltd.). Two inclined shafts were sunk, the No. 1 in the footwall toward the west end of the orebody for exploration and the No. 2, a three compartment shaft, at the east end of the orebody for production. Levels were established at 30 m (100 ft.), 91 m (300 ft.) and 152 m (500 ft.) and drifts were driven along the footwall contact. Difficulties in estimating grade became apparent early in development, because, although the host rock carried low gold values, potential ore required the presence of cross-cutting quartz veins which contained elevated but erratic gold values.

With initial stope development in mid-1938, mined grade proved significantly lower than reserve grade and additional underground drilling was undertaken. The new reserve figures, while much reduced in grade from 4.8 g/t (0.14 oz./ton) to less than 2.4 g/t (0.07 oz./ton), still provided sufficient encouragement to uphold the production decision and a 1000 t/day mill began operation in June 1939. The first gold brick was poured on August 15 of that year. Between 1939 and 1942, the mine produced 1868 kg (64,066 oz.) of gold from ore grading 1.55 g/t (0.0452 oz./ton) Au, at a cost of $1.50-2.00 per ton.

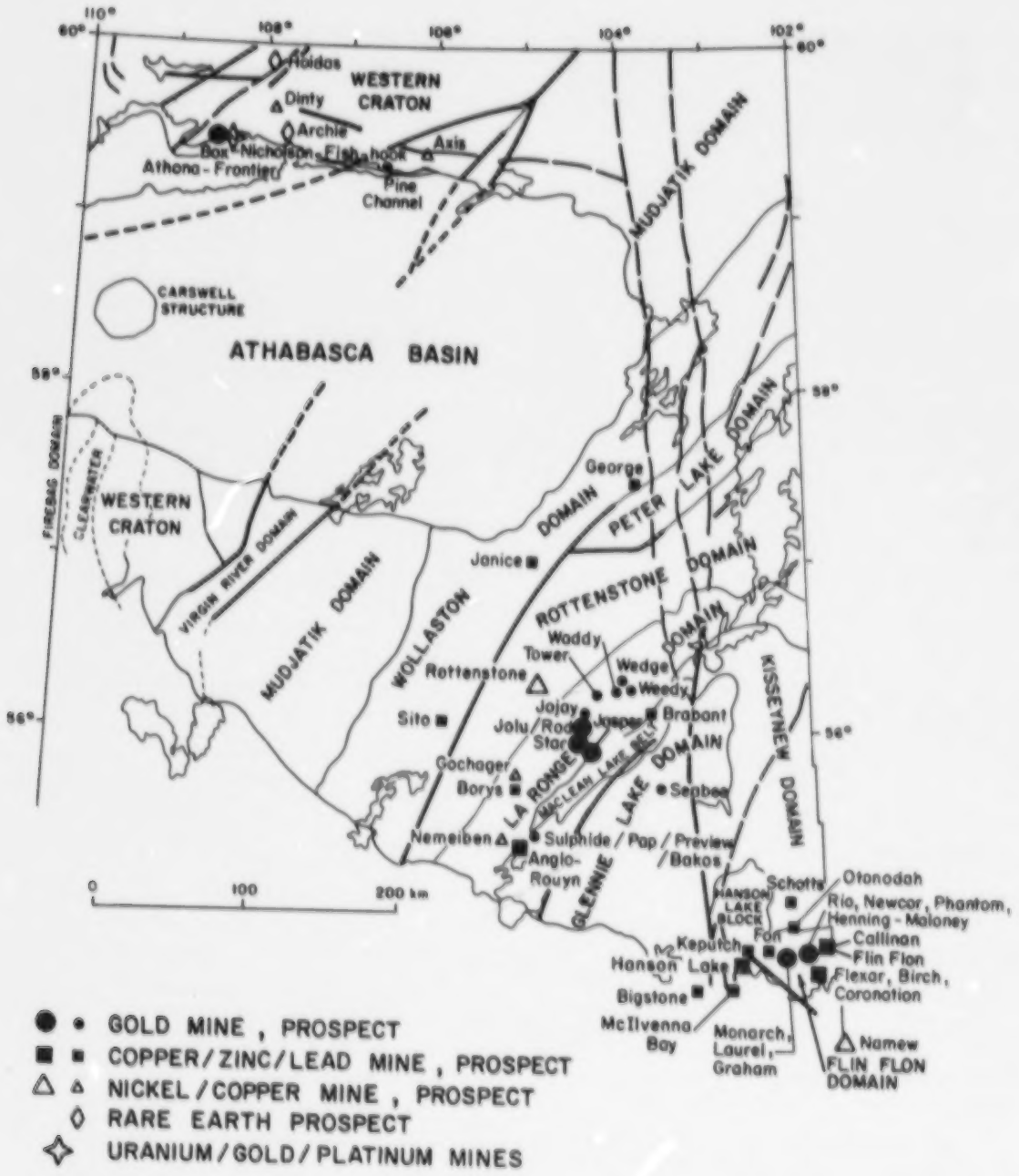


Figure 22 - Major gold, base metal, rare earth and uranium-gold-platinum mines and prospects and tectonic subdivisions of the Saskatchewan Shield. Major shear zones labelled as in Figure 21.

The Box Mine property was re-evaluated by a consortium of companies from the Kasner Group in 1987-89 through an extensive drilling and bulk surface sampling program. In 1990 new geological reserves of 22 673 000 t grading 1.85 g/t (0.054 oz./ton) Au were announced for a potential 265 m deep open pit on the site of Box Mine.

The deposit is contained within a sill-like body of pyritic peraluminous granite, cut by a stockwork of gold-quartz veins. It is 800 m long, 37 m in average width, dips

Table 10 - Published Reserves from Selected Saskatchewan Gold Properties.

Owner(s)*	Property	Reserves(t) (Unstandardized)	Grade g/t	Grade oz./ton
Cameco-Starrex -Uranerz Expl. Min.	21 zone (Star Lake Mine)	208 650	17.2	0.5**
Cameco-Shore Gold Cameco-Uranerz Expl. Min.-Westward	Jasper Mine Contact Lake, Bakos zone	163 300	16.1	0.47***
	BK1+2	1 322 400	8.2	0.24
	BK3	250 000	12	0.35
	Pap SW	493 700	12.4	0.36
Cameco-Golden Rule Res.-Goldsil Res.	Corner Lake	136 100	16.1	0.47
Cameco-Husky Oil	Laurel Lake	387 000	11.3	0.33
Claude Res. Inc.	Seabee	1 034 200	13.7	0.4
Corona Corp.-Int Mahogany Corp.	Rod (Jolu Mine)	376 480	13.7	0.4***
	Mallard	18 350	22.7	0.66**
Golden Rule Res.	Niko	85 730	6.2	0.18
Golden Rule Res. -Goldsil Res.- Comaplex Res.	Tower East	538 000	6.9	0.2
RJK Mineral Corporation	Athona Mine	4 500 000	1.89	0.055
	Box Mine	22 675 000	1.85	0.054
Radcliffe Res. Inc.	"North" Lake	2 360 000	2.4	0.07
Tyler Res.- Golden Rule Res. -Cameco	Weedy B	314 000	4.8	0.14
	Golden Heart	665 000	8.2	0.24
Waddy Lake Res.	Komis	509 850	14.7	0.43
	EP	227 000	5.8	0.17

* Operator first
** Mined out
*** Reserves depleted by production

moderately to the southeast and is enclosed by overlying foliated granite and underlying quartzite.

The quartz veins include sulphides and gold together with albite, tourmaline and chlorite. The veins vary from microscopic dilational gashes to planar bodies several centimetres in width and traceable over many metres. They are typically closely confined within the host granite. Wall-rock alteration is not apparent adjacent to veins, although retrograde chlorite grade metamorphism apparently accompanied vein formation. Gold, typically associated with pyrite, sphalerite and chalcopyrite, occurs primarily in the quartz veins, but also in the wall rock. It is found free, in pyrite and as coatings on microfractures.

Star Lake Mine (Plate 10)

The Star Lake Mine (21 zone) is owned jointly by Cameco Corp. (50%), Starrex Mining Corporation (35%) and Uranerz Exploration and Mining (15%). The history of the area, 135 km northeast of La Ronge and 10 km west of Highway 102, dates to 1961 when prospector E. Partridge staked the Kahn claims over quartz veins from which he had panned gold. Two veins, named the Kahn 18 and 28, were trenched and one drill hole put down under the 18 vein. Also in 1961, M. and E. Hird staked claims to cover an adjacent zone of mineralization, the Rush (Pie) zone. In 1981, the property was acquired by a Saskatchewan Mining Development Corporation - Phoenix Canada Oil Company Ltd. (later Starrex Mining Corporation Ltd.) joint venture, and exploratory drilling was carried out on the 18 vein. Follow-up drilling in 1983 led to discovery of the adjacent 21 zone. Reserves in 1984 totalled 208 650 t grading 17.1 g/t (0.5 oz./ton) Au at a cut-off grade of 3.4 g/t (0.1 oz./ton) to a depth of 130 m. An additional 17 000 t of reserves grading 10.2 g/t (0.32 oz./ton) Au were identified in the Rush zone.

Development of the 21 zone began in late 1985 with sinking of a decline. Mining was by the blasthole open stope method supplemented by shrinkage. Start up of the 200 t/day mill took place in late 1986 and the first full gold bar of 712 oz. was poured on January 23, 1987. In 1987 production was 33,126 oz., and in 1988 was 33,688 oz. gold. Mining was completed in late 1988, feed for the mill for the first quarter of 1989 being provided by the nearby Rush zone. Total production was 76,947 oz. gold from 180 303 t of ore at a recovery rate of approximately 93 percent.

The 21 zone orebody occurred within a northeasterly-trending structural zone in the composite Star Lake Pluton. This pluton ranges in composition from dioritic at the margins to granitic at the core. Mafic dykes and inclusions of the surrounding predominantly basic to intermediate metavolcanics are characteristic of the quartz monzonitic phase which hosted the orebody.

The structural zone dips steeply to the northwest, is around 50 m wide in the vicinity of the mine, and comprises variably deformed quartz-monzonite exhibiting both planar and linear tectonite fabrics. The lineation on shear surfaces plunges steeply to the southwest.

The orebody occurred close to the footwall of the shear zone in mylonites representative of the most strongly deformed rocks within the structure. It comprised massive quartz veins containing disseminated pyrite and gold, had a strike length of 80 m, depth extension of

Plate 9 - Box Mine, 1952 (courtesy of Saskatchewan Archives Board, Photo No. R-B 5755).

Plate 10 - Star Lake mill under construction, 1986.

180 m and maximum width of 14 m. The orebody plunged to the southwest at approximately 60°. There is no visible wall rock alteration to the mineralization. Gold occurred free as very fine grains included in broadly equal quantities of quartz and pyrite.

The Kahn 18 zone is located in an adjacent parallel structural zone, but is of different style, being marked by intensely sheared 'ribboned' rather than massive 'late' quartz. Milled and attenuated sulphide grains are also characteristic of this zone.

Other gold occurrences in the Star Lake area also appear closely related to the Star Lake Pluton and are found at the contact with the country rocks, as at the Mallard Lake and Tamar occurrences, or within the pluton as at the Rod, Rush (Pie), Kahn 18, 21 and Blindman zones. In many of these there is a clear association with northeast-trending structural zones.

Jolu Mine

The Jolu or Mallard Lake property is located in the Star Lake area of the La Ronge Domain, 3 km north of the 21 zone. Cominco Ltd. acquired the property in 1944, discovered the Mallard Lake gold deposit by prospecting and identified through drilling about 23 000 t of ore grading around 20.6 g/t (0.6 oz./ton) Au. Decade Development optioned the property in 1972, and attempted commercial production, extracting a small amount of gold from underground between 1973 and 1976. Mahogany Minerals Resources Inc. acquired the property in 1982, however no significant exploration was undertaken until 1984, when Goldsil Resources Ltd. obtained control of Mahogany. An exploration program was initiated which confirmed and increased reserves in the Mallard Lake zone, but more importantly led to discovery of the new, Rod Main and Rod South zones of mineralization.

Royex Gold Mining Corporation developed an interest in the property in 1985 initially by providing exploration funding in return for shares in Canadian Premium Resources Corporation which had acquired an option to earn a 50 percent interest in Jolu in June 1985. In 1987, through restructured agreements, Royex became operator of the property with a 30 percent direct interest. On July 1st 1988, Royex, by amalgamation with International Corona Resources Ltd., Lacana Mining Corp., Mascot Gold Mines and Galveston Resources Ltd. became Corona Corporation. Underground development was initiated in 1987 and a decline driven to the 170 m level, and then to the 290 m level to prove up reserves. The $18.3 million, 400 tpd mine/mill complex achieved first production with the pouring of an 1130 oz. gold brick on November 15, 1988. Total production to the end of 1990 has been 159,986 oz. of gold from 353 284 t of ore at a head grade of 0.422 oz./ton gold and cost of US $160/oz. Reserves to the 450 m level were estimated 377 000 t grading 13.7 g/t (0.4 oz./ton) Au on January 1, 1989 in the Rod zones and 18 350 t grading 22.7 g/t (0.66 oz./ton) in the Mallard Lake zone. Reserves remaining on January 1, 1991 were 102 000 t grading 12.0 g/t (0.35 oz./ton).

The geological setting at the Jolu Mine is similar to that of the adjacent Star Lake 21 zone property. The composite Star Lake Pluton which ranges in composition from granite in the core to diorite in the margin, intrudes Lower Proterozoic (ca. 1875 Ma) mafic to felsic volcanic flows and pyroclastics and interlayered sediments (biotite schists), metamorphosed to lower amphibolite facies grade.

Gold-quartz mineralization in both the Rod Main and Mallard Lake zones is structurally controlled within 060° trending shear zones marked by mylonites, particularly apparent in the Star Lake Pluton. Intersection with more northerly-trending 035° fracture systems is possibly significant. The plunge of the gold-quartz mineralization varies from 30°SW in the Rod-Main zone to 12°SW in the Mallard zone. These compare with a plunge of 60°SW for the Star Lake 21 zone mineralization located in a similar northeasterly-trending shear zone in the Star Lake Pluton.

The Rod-South and Lake vein at Mallard Lake are gold-quartz vein filling of 080° trending tension gashes.

The gold-quartz mineralizations in these zones are characterized by pyrrhotite, pyrite and chalcopyrite. Visible gold is common and usually associated with molybdenite. At Mallard Lake there is also significant tourmaline. Gold values tend to be erratic, in part due to the

coarseness of the gold, however the tension fracture style of mineralization appears more consistent and of higher grade. There is no significant alteration halo apparent around the zones of mineralization.

Jasper Mine

The Jasper Mine is located in the La Ronge greenstone belt 135 km north of La Ronge and 4 km south of the Star Lake Mine. It was discovered in June 1987 on the Fork Lakes property of Cameco (36%), Golden Rule Resources Ltd. (30%), International Mahogany Corporation (19%) and Shore Gold Fund (15%). The discovery was made during a systematic mapping and prospecting program focussed on the Island Lake Pluton, which had been identified as geologically similar to the nearby Star Lake Pluton, the host to the Star Lake 21 zone and Jolu mines. Diamond drilling of 23 holes (2680 m) in 1987 and a further 63 holes (13 700 m) in 1988 was undertaken to prove up ore reserves in the Jasper discovery zone and adjacent mineralized structures (Roxy and Muskeg zones). At the same time exploration was ongoing on the adjacent Transom Lake property to the south, which contained a mineralized extension of the Jasper structure, referred to as the James zone.

Underground exploration was initiated in July 1988 to prove up mineable reserves in the combined Jasper-James orebody, with the sinking of a 150 m deep decline and development on the 45, 90 and 150 m levels. A production decision was made in December of 1988; however, disagreement among the joint venture partners as to a production plan caused operations to be suspended through 1989. A change of ownership to Cameco (80%) and Shore Gold Fund (20%) was negotiated for both the Fork Lake and Transom Lake properties in late 1989 and this decision allowed production to be achieved in April 1990. At this time mineable reserves were estimated at 163 000 t grading 16.1 g/t (0.47 oz./ton) Au, total production at 85,000 oz. and mine life at two years. Ore processing is at the nearby refurbished 230 tpd Star Lake mill.

The Jasper gold deposit is structurally controlled within a northeasterly-trending shear zone in the granitic-granodioritic Island Lake Pluton. The shear zone is steeply dipping, exhibits an anastomosing horsetail-like configuration and hosts several ore shoots with steep northerly plunges.

The Jasper-James and Muskeg zones occupy the main structure, whereas the Roxy zone to the north occurs in a NNE-trending splay. Gold and accompanying sulphide mineralization are hosted by sheared mylonitized granite and early 'cherty' quartz veins and by later massive quartz veins. The gold in the mineralized zones generally occurs in silicate aggregates, although it is also present within pyrite. Pyrite is the dominant sulphide and is accompanied by accessory marcasite, galena, sphalerite and chalcopyrite and traces of tetrahedrite, covellite, bornite and pyrrhotite. Adjacent to auriferous zones and within the shear zones generally, alteration is marked by muscovite, sericite, chlorite and tourmaline. Hanging wall and footwall rocks comprise undeformed massive granite commonly in sharp contact with the mineralized shear zones.

Bakos Zone

The Bakos zone is jointly owned by Cameco (50%), Uranerz Exploration and Mining Ltd. (30%) and Westward Exploration Ltd. (20%). It is located in the La Ronge greenstone belt near Sulphide Lake, where gold exploration has been ongoing since Adolph Studer began prospecting the area in 1932. Numerous gold occurrences representing several different types of gold mineralization have been discovered over the years; however, none has been as large as the Bakos zone, which currently ranks as the most significant discovery in northern Saskatchewan.

The Bakos zone was found by a combination of exploration techniques, including lake sediment and bulk till geochemistry, followed up by prospecting and diamond drilling. Gold mineralization was located in the summer of 1987 during the prospecting of a poorly exposed structural lineament at the apex of a bulk till gold anomaly. Drilling, in 1988, 1989 and 1990, led to definition of a potentially economic gold deposit open along strike and at depth within the structure and formed the basis for a mine feasibility study.

The Bakos zone occurs within a regional shear zone which cuts granitic and granodioritic phases of the Little Deer Pluton. The shear zone strikes at 070° and dips at 60° to the southeast. Segments of the structural zone are pyritized, sericitized and locally hematized. The gold mineralization is typically present within the altered shear zone adjacent to the structural hanging wall. The mineralized intervals vary from 1.5 to 15 m in width, and contain from 1 to 5 percent, millimetre to centimetre scale quartz and sulphide veinlets. The sulphides are pyrite > > chalcopyrite > pyrrhotite, galena and trace amounts of sphalerite, molybdenite and chalcocite. Visible gold is common. The average Au:Ag ratio is 1:1.

A preliminary feasibility study describes mineable reserves within the BK 1 and BK 2 zones of the Bakos structure to be 1 322 400 t grading 8.2 g/t (0.24 oz./ton) Au or an estimated 338,310 oz. of recoverable gold to a depth of 250 m. The recently drilled BK 3 zone within the Bakos structure shows possible reserves of 250 000 t grading 12 g/t (0.35 oz./ton) Au containing 96,000 oz. Au. The newly discovered Upper Structure, lying 40 to 60 m south of the Bakos structure in the area of the BK 3 drilling, holds considerable potential for additional reserves. High gold values were intersected in 5 holes in this new structure, four of which averaged greater than 34.3 g/t (1 oz./ton) Au over significant widths. Hole TU.90 - 146 returned 405 g/t (11.81 oz./ton) Au uncut across 4.5 m, while hole TU.90 - 148 returned 52.5 g/t (1.53 oz./ton) Au uncut across 3 m. These intersections are 150 m apart and are the deepest on the new structure at 180 m vertical depth. Cut gold values for the two intersections quoted are 4.5 m at 13.0 g/t (0.38 oz./ton) Au and 3 m at 22.0 g/t (0.64 oz./ton) Au.

Under the feasibility plan, mining will primarily be by blast hole stoping with minor shrinkage in narrow

zones. Primary access will be by decline with ore hoisted through a production raise. The ore is free milling and a conventional 635 tpd cyanide leach plant with carbon in pulp recovery is planned, with expected recoveries in excess of 95 percent. Current estimates for the project are capital cost $39 million, annual production 64,000 oz. Au, operating costs $250/oz. and a six year mine life.

Seabee Mine

The Seabee deposit, located on the prominent peninsula at the northeast end of Laonil Lake, was staked in 1949 by Cominco. Over the next 35 years Cominco drilled 117 holes and dug several trenches to evaluate the gold content of the mineralized veins. Claude Resources purchased the property in 1984, completed some additional drilling and carried out an ore reserves study. In 1985, Placer Development Limited entered into an agreement with Claude to gain a 55 percent interest in the property. By early 1987 Placer had completed 72 additional diamond drill holes, as well as extensive overburden stripping, detailed sampling and remapping of the property. Subsequently, during 1987, Placer completed an underground exploration program that included 900 m of underground development, bulk sampling and 6200 m of underground drilling. In 1988 Placer terminated its joint venture agreement with Claude, In late 1988, Claude commissioned ACA Howe International Ltd. to complete an ore reserves study. This investigation concluded that the main zone, comprising veins 2 and 5 contained proven and probable ore reserves of 585 135 t grading 12.5 g/t (0.36 oz./ton) Au and possible ore reserves of 332 937 t grading 12.5 g/t (0.36 oz./ton) Au. In late 1989 Claude engaged Cominco Engineering Services Limited (CESL) to manage a $2 million program to include 3960 m of diamond drilling, an additional 300 m of underground development and bulk sampling. On May 15, 1990, on the basis of the final feasibility study by CESL which reported reserves (all classes) of 1.03 million tonnes grading 13.7 g/t (0.4 oz./ton) Au, Claude announced a decision to proceed with production. Mine development presently in progress, will include a 360 tpd mill, at an estimated cost of $22 million. The mine is expected to have a 5 year life and an annual gold production of 48,000 oz. at a cost estimated at US $210 per oz.

Seabee ore is hosted in northeasterly-trending shear zones in the Laonil Lake Intrusive Complex, which, in the vicinity of the veins, comprises a series of gabbroic layers or sheets cut and commonly capped by quartz diorite. Ultramafic layers or lenses lie at the base of some sheets. Intercalated or rafted within the intrusive are variably thick layers, lenses and xenoliths of mafic metavolcanics and occasionally of metagreywacke, and the complex is cut by ultramafic and intermediate dykes. This whole assemblage is metamorphosed to amphibolite facies grade.

Ore is hosted in discontinuous quartz-tourmaline veins confined to a series of east-northeast-trending near-vertical shear zones. The veins are isoclinally folded about axes which plunge steeply west-southwest parallel to a penetrative mineral lineation. Individual shears are up to 200 m long. Narrow sulphide-bearing feldspar porphyry bodies, within and adjacent to the shear zones, appear genetically associated with the quartz veins. The shear zones are thought to be contemporaneous with the major Laonil Lake Shear Zone which forms the southern contact of the Laonil Lake Intrusive Complex with the diapirically emplaced Eyahpaise Lake Pluton. Although visible gold is present in the quartz veins, gold is more abundant in fine-grained pyrite and chalcopyrite. Other minerals in the veins include pyrrhotite, tourmaline, tellurides, magnetite, actinolite-tremolite, sericite, sphalerite, molybdenite and barite. In and adjacent to the shear zones, there is a pervasive potassic alteration halo marked by the appearance of biotite in place of hornblende. Sulphidation and irregular carbonatization have also been documented.

Laurel Lake North Zone

Gold exploration on the west side of Missi Island in Amisk Lake dates to 1932 when S. Russick and associates staked nine claims and dug a few trenches. Periodic trenching and limited shallow drilling between 1941 and 1960 principally by Nesnah Mining and Exploration Company and R. Singebeil and associates exposed seven gold zones around the south end of Laurel Lake.

In 1982, prospecting and geological mapping by Saskatchewan Mining and Development Corporation (now Cameco) outlined an arcuate belt of highly altered gold-enriched felsic fragmental volcanics and flows extending from Baby Gull Island to the north end of Laurel Lake. In 1983, follow up drilling of geochemical and I.P. chargeability highs along this trend intersected significant gold-silver mineralization, and subsequently led to definition of probable and possible reserves of 256 000 t grading 15.1 g/t (0.44 oz./ton) Au and 75.4 g/t (2.2 oz./ton) Ag to a depth of 300 m.

In 1988 the deposit was examined underground with a 890 m long decline, 397 m of drifting and 2082 m of underground diamond drilling, to establish probable geological reserves of 387 000 t grading 11.3 g/t (0.33 oz./ton) Au. However, the orebody was judged too complex geologically for economic extraction. The property is currently owned by Cameco (50%) and Husky Oil Operations Ltd. (50%).

The North Laurel Lake Au-Ag zone appears to comprise a steep westerly dipping system of high grade sulphide rich feeder veins hosted by a massive strongly altered quartz-porphyritic rhyolite intrusive and a west-northwest-trending system of lower grade sulphide disseminations and stockworks developed in altered coarse porphyritic felsic fragmentals, tuffs and porphyritic flows on the western flank of the intrusive. The feeder vein system comprises three mineralogically distinct zones, which are, respectively, Pb-Zn rich in the southwest, Cu-rich in the centre and Ag-rich in the northeast. Both systems are open along strike and down dip.

The majority of the gold appears to occur free as fine grains and as veinlets within pyrite, while the silver is carried by tennantite-tetrahedrite particularly in the north-

northwest-trending feeder vein system. Additional sulphides include sphalerite, galena, and chalcopyrite primarily in the feeder vein system. The average sulphide content of both systems is only in the one to three percent range. Near surface (down to 60 m), the sulphides are strongly oxidized.

An extensive alteration halo consisting principally of sericitization, bleaching and development of a bright green mica surrounds the mineralized zones. This halo is up to 100 m wide in the west-northwest system, but much tighter, up to a few metres wide, in the north-northwest feeder system.

The style of mineralization, wall-rock alteration and the associated trace elements, in particular, As, Sb, Ag and Zn, suggest an epithermal mode of origin.

Base Metals

Base metal production in the province has been dominated by the Hudson Bay Mining and Smelting Co. Ltd. copper-zinc mine straddling the Saskatchewan-Manitoba border at Flin Flon. Since 1930, to the end of 1990 a total of 62 475 304 t of ore have been extracted from this world class orebody, of which 43 133 255 t have been from Saskatchewan. In 1989 production effectively ceased with depletion of the orebody and the mine and few remaining ore reserves are being utilized for miner training. Gold, silver, tellurium, selenium and cadmium were byproduct metals recovered with the copper and zinc. Between 1957 and 1972, several smaller mines operated for short periods of time. Of these, the Birch, Coronation and Flexar were primarily copper producers developed by Hudson Bay as satellites to the main Flin Flon orebody, although the Coronation ore had significant zinc, silver and gold. The Anglo-Rouyn mine of Rio Algom Mines Ltd. at Moose Point on Lac La Ronge yielded copper and byproduct gold and silver between 1966 and 1972. Western Nuclear Inc. produced zinc, lead, copper and some silver from the Hanson Lake Mine, located 85 km west of Flin Flon, between 1967 and 1969, and Rottenstone Mining Ltd. mined the Rottenstone deposit seasonally between 1965 and 1968. This deposit, located 145 km north of La Ronge, has been Saskatchewan's only nickel producer. It yielded, in addition, copper and byproduct precious metals, platinum, palladium, gold and silver. Production from these mines is summarized in Table 11.

The distribution of base metal deposits in Saskatchewan reflects a difference in crustal character between the northwestern and southeastern segments of the Precambrian Shield. The southeastern segment between La Ronge, Flin Flon and Lynn Lake (in Manitoba) is interpreted as a Lower Proterozoic ensimatic regime between the Superior Craton in the southeast and the "Churchill Craton" in the northwest. It comprises volcanoplutonic arc material (e.g. La Ronge and Flin Flon metavolcanic belts), interarc and back-arc basin sediments and possibly exotic or suspect terrains represented by arc and microcontinental fragments. There is a marked contrast with the ensialic regime of the "Churchill Craton" and the overlying thick Lower Proterozoic shelf-type metasediments of the Wollaston Group.

The ensimatic regime is host to essentially volcanogenic metal deposits: 1) proximal volcanic-hosted massive sulphides of Cu, Cu-Zn, Zn and Pb-Zn epitomized by the Flin Flon orebody and 2) distal, sediment-hosted deposits of Cu, Cu-Zn and Zn exemplified by the Anglo-Rouyn Mine, Brabant Lake and Borys Lake deposits.

In contrast, the Wollaston Group is host to essentially sedimentogenic deposits: 1) quartzite-hosted Zn-Pb at George Lake and Sito Lake, 2) arkose-hosted Cu±Pb, Ag, Au 'red bed' type copper at Janice Lake, and 3) arkose-, black shale (metapelite)- and calcareous sediment-hosted 'syngenetic' uranium deposits. These have not proven to be of economic grade.

Major economic magmatogenic Ni±Cu deposits are unknown in Saskatchewan, although, just beyond the Manitoba border, there are the significant Lynn Lake deposit in the strike extension of the La Ronge metavolcanic belt, and the Namew Lake deposit in the Flin Flon belt. In Saskatchewan, only the small Rottenstone deposit has proved economic, largely on account of its extraordinarily rich precious metals content. Subeconomic reserves have been identified in mafic and ultramafic bodies of various origins in both the Archean and Lower Proterozoic, such as those at Nemeiben and Gochager Lakes northeast of La Ronge and at Axis and Dinty Lakes north of Lake Athabasca (Table 12).

Table 11 - Saskatchewan Base and Byproduct Metal Production

Mine	*Year*	*Tonnage*	*Cu*	*Zn*	*Pb*	*Ni*	*Au*	*Ag*	*Pt*	*Pd*	*Se + Te*	*Cd*
Flin Flon (Total)	1930-90	62 475 304			not available							
Flin Flon (Sask)	1930-90	43 133 255[1]			not available							
Birch Lake	1957-60	279 750	15 309 383	18 398	—	—	25	857	—	—	19 611	34
Coronation	1960-64	1 391 750	48 969 997	2 249 945	—	—	2 335	5 208	—	—	53 543	5 053
Rottenstone	1965-68	26 058	—	—	—	654 118	11	91	63	112	—	—
Anglo-Rouyn	1969-72	1 717 150	28 777 038	—	—	—	2 104	9 586	—	—	—	—
Western Nuclear	1967-69	147 359	526 461	8 636 968	5 537 862	—	31	11 785	—	—	—	—
Flexar	1969-72	306 000	11 447 391	—	—	—	229	—	—	—	—	—

Tonnage in tonnes, metals in kilograms

[1]Average grade of ore for the Flin Flon Mine (Saskatchewan portion) reported as 2.21% Cu, 4.17% Zn, 2.5 g/t (0.073 oz/ton) Au, 42.2 g/t (1.22 oz/ton) Ag.

Table 12 - Base Metal Reserve Estimates

Deposit	Tonnage (t)	Cu %	Zn %	Pb %	Ni %	Au g/t (oz./ton)	Ag g/t (oz./ton)
Flin Flon Mine (Total)	42 314	2.48	1.7	-	-	0.75 (0.022)	14.1 (0.41)
Flin Flon Mine (Sask. Portion)	38 817	2.39	1.8	-	-	0.75 (0.022)	14.1 (0.41)
Mcilvenna Bay							
Lens 1	816 000	2.23	0.94	0.03	-	0.74 (0.02)	15.3 (0.45)
Lens 2	9 800 000	0.9	5.76	0.42	-	0.49 (0.015)	24.7 (0.73)
Lens 3	40 000	1.6	8.1	-	-	-	-
Callinan	788 410	1.28	3.7	-	-	1.50 (0.045)	16.8 (0.49)
Otonodah	120 000	2.8	1.2	-	-	0.55 (0.16)	7.9 (0.23)
Fon			(not available)				
Schotts	1 982 750	0.81	1.35	-	-	-	-
Keputch	739 000	2.15	1.77	-	-	0.1 (0.003)	7.9 (0.23)
Bigstone	1 451 000	2.9	-	-	-	-	-
	308 000	-	11.2	-	-	-	-
Brabant	3 927 000	0.64	4.32	-	-	-	-
Borys			(not available)				
George	4 535 000	-	2.65	0.35	-	-	-
	(incl. 2 630 000	-	3.67	0.53)	-	-	-
Nemeiben	1 450 000	0.42	-	-	0.81	-	-
Gochager	4 660 000	0.08	-	-	0.31	-	-
Axis	1 360 000	0.04	-	-	0.94	0.34 (0.01)	3.4 (0.1)
Dinty	1 360 000	-	-	-	0.6	-	-

Flin Flon Mine (Plate 11)

In 1927, the Hudson Bay Mining and Smelting Co. Ltd. set up a pilot mill near the Flin Flon copper-zinc discovery staked by Thomas Creighton and the Mosher and Dion brothers in 1915. From 1916 to 1918, 44 diamond drill holes totalling 7822 m outlined the deposit to 274 m below surface. In 1920 two shafts were sunk 150 m apart, the No. 1 shaft to 64 m and the No. 2 to 93 m, and drilling was completed on the 30 m, 61 m and 91 m levels.

In 1921, the Mining Corporation of Canada acquired a majority interest in the property and carried out exploration work in the vicinity of the deposit. In 1925 the Witney Group of New York optioned the property and in 1926-27 set up a test mill. In 1927 Witney established a majority interest with the Mining Corporation of Canada retaining 15 percent. In the same year the Hudson Bay Mining and Smelting Company Limited was incorporated to develop the property. The development of the mine and construction of the mill, zinc recovery plant and copper smelter, as well as the hydroelectric plant at Island Falls on the Churchill River and the railway line from The Pas, began in 1928. Production was achieved in 1930.

Mining was initially by open pit (792 x 137 m) to a depth of around 100 m. After 1937, the emphasis shifted to underground and since 1941 has been wholly so. Production started at 2700 t/day and reached a high of 5400 t/day during World War II. The mine has three vertical shafts; the original 676 m North Main (No. 1) shaft in Manitoba, and in Saskatchewan the 1241 m South Main (No. 2), 1.6 km to the south and the 991 m No. 3 shaft located 715 m south-southwest of the No. 1 shaft. In recent years, the South Main has been the main production shaft and it continues to be utilized for hoisting ore from the newly opened Callinan zone. Mine workings extend to the 1125 m level and the ore zone disappears below 1140 m.

The reserves were originally estimated at 16.3 million tonnes grading 1.71 percent Cu, 3.5 percent Zn, 2.5 g/t (0.074 oz./ton) Au and 36.3 g/t (1.06 oz./ton) Ag. To the end of 1990, 62 million tonnes grading 2.17 percent Cu, 4.13 percent Zn, 2.5 g/t (0.077 oz./ton) Au and 41.5 g/t (1.21 oz./ton) Ag have been extracted. Since 1962 production has been from pillars and remnants.

The mine area is underlain by Lower Proterozoic metavolcanics of the Amisk Group, which are steeply easterly dipping and facing. Footwall rocks to the west of the deposit comprise a thick sequence of mafic pillowed flows and fragment breccias. The immediate footwall to the deposit is a 200-300 m thick sequence of pillow fragment breccia. Immediately overlying, to the east

Plate 11 - Flin Flon Mine open pit and South Main headframe, 1960 (Courtesy of Saskatchewan Archives Board, Photo No. R-B 4959(2)).

is the 'Mine Rhyolite' that hosts the deposit. This unit, up to 150-180 m thick in the vicinity of the smelter complex, can be traced along strike for about three kilometres and comprises two distinct phases: a lower quartz- and plagioclase-phyric flow breccia and an upper massive, flow banded quartz- and plagioclase-phyric rhyolite flow overlain by flow breccia that commonly contains slabs of flow banded rhyolite.

The Mine Rhyolite (and related sulphide bodies) is immediately overlain by bedded volcaniclastic rocks comprising rhyolite clast-bearing debris flows, which, in turn, are overlain by a thick, relatively uniform succession of porphyritic, pillowed mafic flows. Subvolcanic sills and dykes of metadiorite intrude the metavolcanics, as do younger, post-volcanic gabbroic bodies (the Boundary Intrusions).

These rocks outcrop in a major anticline that has subsidiary folds on its limbs. The orebodies occur on the eastern limbs and crests of these subsidiary folds and plunge 35° to the southeast parallel to the fold axes. Six orebodies are identified within a zone with a strike length of about 800 m, width of 150 m and depth extension from surface of 1140 m. The zone dips 70° east and plunges at 35° to the southeast over a plunge length of about 2000 m. The orebodies average 270 m in length, 21 m in width, 450 m in depth and 840 m in plunge length. An extensive zone of footwall alteration, comprising chlorite and chlorite-talc schists, is associated with the deposit.

Approximately 70 percent of the ore is contained in massive sulphide lenses that are commonly banded; the remainder is contained in zones of disseminated sulphide adjacent to these lenses. Predominant minerals are pyrite, pyrrhotite, sphalerite and chalcopyrite. Minor minerals include arsenopyrite, cubanite, galena, tetrahedrite-tennantite, sylvanite, tetradymite, altaite, magnetite, electrum and gold.

Sphalerite, galena, tetrahedrite and electrum are enriched relative to chalcopyrite toward the hanging wall portions of the massive sulphide lenses. As well, there is a close association between zinc and gold-silver in the massive sulphide lenses. Also, copper increases in proportion relative to zinc, gold and silver with increasing depth in the mine.

Birch Lake Mine

The Birch Lake deposit, discovered by prospector Joe Brain in 1949, was optioned by the Hudson Bay Mining and Smelting Co. Ltd. that year, and diamond-drilled in 1951-52. Development work between 1952 and 1956 consisted of drilling, the sinking of a 502 m, three compartment shaft and lateral work on six levels. Production commenced in 1957 and continued until 1960 when the ore was exhausted. Ore was trucked to the nearby Coronation Mine and then hauled to Flin Flon by company railway. Total production was 278 690 t grading 6.17 percent Cu, 0.1 g/t (0.003 oz./ton) Au and 4.1 g/t (0.12 oz./ton) Ag. Some zinc, selenium, tellurium and cadmium were also produced.

The orebody occurred in sheared andesitic Amisk volcanics (chlorite schists), as a series of tabular massive sulphides with an average width of 2 m and lengths of 45 m to 90 m. It comprised mainly chalcopyrite, pyrrhotite and pyrite with lesser amounts of magnetite and sphalerite. Contacts with surrounding meta-andesites were sharp, alteration being confined within the zone of shearing, which extended for only a short distance on either side of the orebody.

Flexar Mine

The Flexar Mine site is located 1.5 km to the north of the Birch Lake Mine and appears to lie within the same structure. The property was acquired by Hudson Bay from prospector Joe Brain in 1952 and drilled, thereby outlining a small copper deposit. In 1963, a power line was extended to the property, mine development initiated and a shaft sunk to 356 m. The shaft was deepened to 418 m in 1968 and the mine brought into production in 1969. The orebody was exhausted in 1972, after yielding 305 940 t grading 3.75 percent Cu, 0.47 percent Zn, 1.4 g/t (0.04 oz./ton) Au and 8.9 g/t (0.19 oz./ton) Ag.

The geological setting of the Flexar deposit is similar to that of Birch Lake. Ore occurred in chlorite schist and comprised chalcopyrite, pyrrhotite, pyrite, magnetite and sphalerite.

Coronation Mine

The Coronation deposit was discovered in 1953 by the Hudson Bay Mining and Smelting Co. Ltd. through diamond-drilling of an electromagnetic anomaly. In 1955-56, sinking of a 3-compartment shaft to a depth of 455 m was undertaken and levels were established at 46 m intervals. An adjacent 2-compartment shaft was sunk to 322 m in 1958 and underground drilling carried out to establish reserves. From 1960 until depletion of the orebody in 1965, the mine produced a total of 1 281 465 t grading 4.25 percent Cu, 0.3 percent Zn, 2.0 g/t (0.059 oz./ton) Au and 4.8 g/t (0.14 oz./ton) Ag. Production was higher than the initially calculated reserves due to discovery of additional ore and through lowering of the cut-off grade during the later stages of mining.

The Coronation deposit occurred in Amisk metavolcanics comprising andesitic flow and breccia and basic tuffs, intruded by granodiorite and gabbro. Three ore shoots occupied a weakly discordant zone of shearing, which had been traced over a length of 6.5 km. They occurred within an envelope of lower grade mineralization 275 m long, up to 37 m wide and over 300 m high. As mined, the deposit was 182 m long, up to 20 m wide and 320 m deep. The ore comprised massive pyrrhotite, pyrite and chalcopyrite, with minor sphalerite and magnetite.

Western Nuclear Mine

During 1956 and 1957, Parrex Mining Syndicate (Trust) acquired by staking and option over 1200 claims near the southwestern shore of Hanson Lake. Airborne

geophysics and ground follow-up outlined an anomaly which was drilled during 1957 to 1960, resulting in the discovery of a "flat-lying" orebody estimated to contain 113 375 t grading around 21 percent combined Pb-Zn. In 1965, the property was purchased by Share Mines and Oils Ltd., who carried out further drilling, thereby increasing reserves to an estimated 229 500 t grading 8.08 percent Pb, 11.42 percent Zn, 0.61 percent Cu, 1 g/t (0.031 oz./ton) Au and 162.5 g/t (4.74 oz./ton) Ag. An agreement was reached with Western Nuclear Inc. for production financing and in 1966 a shaft was sunk to 205 m some 200 m west of the orebody, which lay under Hanson Lake.

Production began in 1967 and lasted until 1969, when the orebody was mined out. A total of 147 301 t was extracted at an average grade of 5.83 percent Pb, 9.99 percent Zn and 0.51 percent Cu.

The deposit was hosted by metavolcanic rocks of Lower Proterozoic age, represented by interlayered dacite, mafic tuff, and quartz sericite fuchsite schists intruded by a sill-like quartz-feldspar porphyry. It was subvertical and northerly-trending and consisted of several high-grade lenses of massive sulphides made up mainly of sphalerite and galena with minor arsenopyrite, pyrite, pyrrhotite, chalcopyrite, argentite, tetrahedrite and gold. The deposit was about 450 m long, from 0 to 10 m wide and plunged 12° to the north.

Anglo-Rouyn Mine

The Moose Point copper showing on Lac La Ronge, discovered by McInnes in 1908, was staked by the Hall brothers in 1915. The Consolidated Mining and Smelting Co. of Canada Ltd. undertook the first trenching and drilling on the property in 1929; however, they dropped their option and eventually, in 1950-51, the property lapsed. Restaking occurred in 1951-53 and the new claims were acquired by Anglo-Rouyn Mines Ltd. Extensive exploration led to underground development in 1955 and by the following year, a shaft had been completed to 186 m and four levels established. By the end of 1956, however, underground activity had been suspended.

Some diamond-drilling was done from surface in 1957, after which the property remained dormant until 1963, when additional claims were staked. Further exploration work was carried out by Rio Algom Mines Ltd. and a decision was made to bring the property into production.

Construction of a mill began in 1965 and the shaft was dewatered and deepened to 244 m. The 900 t/day mill was completed in January 1966 and the first shipment of concentrate made to the Flin Flon smelter by road a month later. Reserves were estimated at 1.8 million tonnes grading 2.4 percent Cu and 0.6 g/t (0.018 oz./ton) Au after dilution.

Underground mining was augmented by two open pits which yielded some 198 600 t, approximately 12 percent of total production. Reserves were exhausted in 1972. Total production was 1 716 770 t at a calculated grade of 1.71 percent Cu, 1.2 g/t (0.036 oz./ton) Au and 5.5 g/t (0.16 oz./ton) Ag.

The deposit was in northwesterly dipping metasedimentary gneisses which are structurally overlain by sheared granodiorite. The metasediments comprise quartzo-feldspathic and intermixed calcareous, diopside-amphibole-epidote-bearing gneisses of uncertain origin. The three ore zones formed en-echelon lenses dipping northwest and plunging gently to the southwest, parallel to a prominent tectonic lineation. Ore zones ranging in width from 0.3 to 10 m comprised stringers and veins of quartz, pyrite, pyrrhotite and chalcopyrite, that averaged more than 2 percent Cu. Magnetite, sphalerite, galena and pentlandite are present in small amounts. Mineralization has been traced along strike for about 8 km to the northeast and the southwest.

Rottenstone Mine

The "hill of rotten stone" close to the shore of Rottenstone Lake, 145 km north of La Ronge, was likely drawn to the attention of trappers Tremblay and Olson by local Indian people. The showing was staked in 1928 and acquired by the Hall brothers, who optioned it to The Consolidated Mining and Smelting Co. of Canada Ltd. This company put down 19 diamond-drill holes but allowed the option to lapse.

Drilling programs were carried out between 1948 and 1962 by three different companies. The additional information, coupled with the rise in metal prices and the construction of a winter road north from La Ronge, provided the basis for a viable mining operation during the non-winter months of 1965 to 1968 by Rottenstone Mining Ltd. Some 26 050 t of Ni-Cu-Pt-Pd-Au-Ag ore were extracted from an open pit to yield 5047 t of concentrate, grading 10.36 percent Ni, 5.74 percent Cu, 3.4 g/t (0.10 oz./ton) Au, 18.2 g/t (0.53 oz./ton) Ag, 11.3 g/t (0.33 oz./ton) Pt and 18.2 g/t (0.53 oz./ton) Pd. Published reserves were estimated at 45 000-55 000 t of 2 percent Ni, 2 percent Cu, 7.5 g/t (0.22 oz./ton) Pt and 5.1 g/t (0.15 oz./ton) Pd. All that remains of the deposit is a flooded pit.

The pyroxenite-harzburgite body that hosted the Hall deposit was confined within a migmatitic gneiss, itself incorporated within a granitoid biotite tonalite/trondhjemite terrane. A second showing, the 'Tremblay-Olson' 2.5 km to the southwest, is apparently geologically similar. The Hall deposit outcropped in a rusty dome of oxidized rocks 46 m in diameter rising 9 m above Rottenstone Lake. Ore was confined to a moderately to gently east-dipping sill-like harzburgite-orthopyroxenite body, approximately 55 m thick. Disseminated and net-textured sulphides constituted 20 to 50 percent by volume. The sulphides were mainly pyrrhotite, pentlandite (or violarite) and chalcopyrite. Minor quantities of cubanite, magnetite, chromite, pyrite and sperrylite were associated. Graphite was disseminated in the gangue and sulphides. Locally the ore was chalcopyrite-rich.

McIlvenna Bay Deposit

The McIlvenna Bay massive sulphide zinc-copper deposit was found in March 1988 by a joint-venture exploration group including Saskatchewan Mining and Development Corporation (now Cameco), Esso Minerals Canada and Tri-Gold Industries (now Trimin Resources Inc.). The property is currently owned by Cameco (67.1%) and Billiton Metals Canada Inc. (32.9%). McIlvenna Bay is located on the southern shore of Hanson Lake and the deposit lies 1 km to the south of the lake. The deposit was discovered by drilling, following an airborne electromagnetic (input) survey and ground magnetometer and HLEM surveys over the airborne conductor. Six holes were completed in early 1988 all of which hit stringer and massive sulphide mineralization. A further 48 holes were put down in late 1988 and 1989 and on this basis reserves calculated at 10.7 million tonnes grading 1% Cu and 5.4% Zn (Table 12). Additional reserves identified by seven holes drilled in early 1990 are not included in this estimate.

The deposit is hosted by Lower Proterozoic age metavolcanics and intrusives capped by a thin (ca. 15 m), unconformable cover of Ordovician quartz sandstones and dolomitic limestones. A few kilometres to the north, Precambrian rocks along strike from the deposit are exposed around Hanson Lake. Here, the metavolcanics comprise predominant dacitic and rhyolitic lavas, pyroclastics and/or epiclastics overlain successively by compositionally mixed volcanics and volcaniclastics interlayered with iron formation and greywackes. Subvolcanic quartz-feldspar porphyry plutons intrude the felsic volcanics and dacite-gabbro sheets the overlying mixed sequence.

In the McIlvenna Bay deposit copper-zinc mineralization occurs in the same volcanic succession as exposed in the north in felsic rocks within metres of the base of the mixed volcanics. Felsic schists which host the mineralization are grey, poorly layered, medium-grained quartz muscovite chlorite schists, which in places contain pale pink porphyroblasts of andalusite. They appear to have been derived by processes of alteration, including chloritization, silicification and argillization, from footwall quartz muscovite (sericite) schists which are in part quartz-phyric, contain siliceous sections and represent sheared rhyolitic volcanics or derived detritus and interlayered cherts.

The deposit, as presently defined, consists of one main lens (No. 2) and at least two smaller lenses (Nos. 1 and 3) of massive sulphides. These dip steeply northeast and plunge moderately to the north. The massive sulphides, typically underlain by copper rich stringer 'ore', comprise essentially unlayered pyrite-sphalerite-chalcopyrite. Pyrite is commonly rounded and coarse-grained and sphalerite and chalcopyrite occur interstitially with minor galena, marcasite and magnetite. The underlying stringer zones are characterized by up to 30 percent copper and iron sulphide concentrations parallel to and cross-cutting schistosity. The massive sulphide lenses range up to 15 m in true thickness and the copper stringer up to 60 m. Mineralization persists over a strike length of at least 600 m and to a depth of at least 900 m.

Rare Earth Elements

Rare earth element (REE) occurrences in northern Saskatchewan are, for the most part, characterized by monazite±xenotime in biotite-rich segregations in pegmatites or adjacent gneisses. Assays typically range from 0.01 percent to 2.0 percent total REE, although two occurrences in the Uranium City area gave values of up to 16 percent total REE.

World production of monazite is primarily from recent beach sands. An ilmenite-monazite occurrence in Archean granulite facies gneisses, at Archie Lake 30 km east-southeast of Uranium City, is thought to represent an ancient metamorphosed deposit of their type. A 5 to 6 m thick stratabound zone has been traced over a strike length of 600 m.

In the Nisikkatch-Hoidas Lakes area, 40 km northeast of Uranium City, allanite-apatite veins are found in a zone up to 10 km long. Grab samples yield assays of up to 12 percent total REE.

The Athabasca Group quartz sandstones and conglomerates contain heavy mineral layers, particularly in the strongly conglomeratic basal section. These layers remain untested for REE-bearing paleoplacer deposits.

Yttrium associated with heavy REE is concentrated in Athabasca Group sandstones at the Maw zone near Williams Lake in the southeastern part of the sandstone basin. Yttrium values of 800 to 5000 ppm are obtained from samples within a zone estimated to contain 336 000 t grading 0.25 percent Y_2O_3. Dravitic tourmalinization and drusy quartz silicification characterize the mineralization. Masses of xenotime containing up to 10 percent Y occur in altered, clay-enriched Athabasca Group sandstones above the McClean Lake uranium deposits. These occurrences, together with enrichments in Y and REE in other Athabasca Basin uranium deposits, suggest a potential for "unconformity-type" diagenetic-hydrothermal Y and REE ore.

Platinum Group Metals

A small quantity of platinum group metals was produced in Saskatchewan between 1965 and 1969 at the Rottenstone Mine. Exploration for these metals is ongoing in several areas. Targets include mafics and ultramafics of Archean and Proterozoic ages throughout the Shield, especially those in which nickel-copper mineralization has been identified. A particular focus has been on the extensive area of mafic rocks known to contain both layered bodies and showings of platinum group metals in the Peter Lake Domain.

A second and potentially new type of target in Saskatchewan is the platinum- and gold-bearing uranium veins of the Nicholson and Fish Hook Bay areas on the north shore of Lake Athabasca. The veins are marked by com-

plex mineralogy and geochemistry, features common to uranium deposits of unconformity type which characterize the Athabasca Basin and to uranium deposits associated with sandstone basins in other areas of the world. Of particular note in this context are the polymetallic uranium occurrences in Late Proterozoic metasediments in the Shaba province of Zaire, as at the Shinkolobwe Mine, and in the Early Proterozoic Coronation Sandstone in the South Alligator River Valley of the Northern Territory of Australia, as at the Coronation Hill Mine. Both deposits exhibit uranium, in association with gold, platinum and other metals.

Industrial Minerals

Industrial minerals have played a significant role in the mining economy of Saskatchewan during the past two decades. Since 1966, the value of production has averaged over 70 percent of total mineral production excluding petroleum and related products and uranium (Figure 23). Although industrial minerals production has grown steadily, and in some cases spectacularly between about 1972 and 1982, the bulk of the growth is attributed to the potash industry. Figures 24 and 25 illustrate the growth in value of sales of the major industrial minerals in Saskatchewan.

Since the rise of the potash industry, industrial minerals have on average contributed about one-third of the value of total production of all mineral substances including petroleum and related products.

Lignite

Extensive lignite resources are mined in the extreme south of the province. There are four mines in the Estevan area, two owned by Manalta Coal Ltd. and two by Estevan Coal Corporation, and one in the Coronach area, operated by Prairie Coal Ltd. (Plate 12).

Lignite sales peaked at over 12 million tonnes in 1986. A decline of over a million tonnes in 1986 was due mainly to the commissioning of the Nipawin hydroelectric plant on the Saskatchewan River and an above average rainfall.

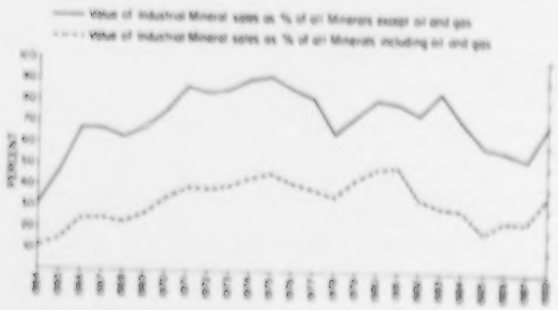


Figure 23 - Contribution of industrial minerals to the value of mineral production in Saskatchewan from 1964 to 1988.

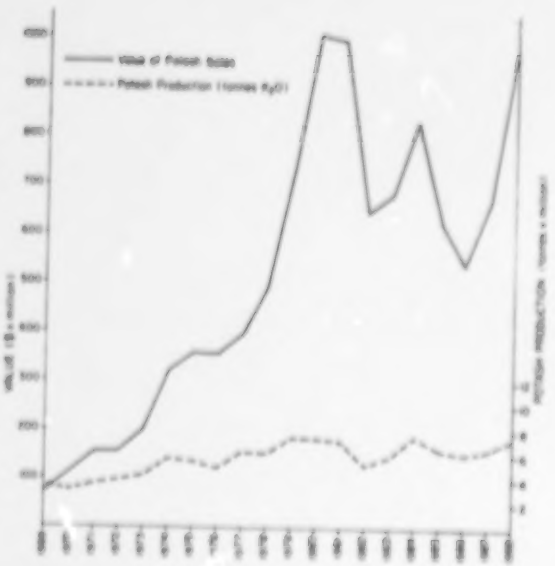


Figure 24 - Potash production in Saskatchewan from 1969 to 1988.

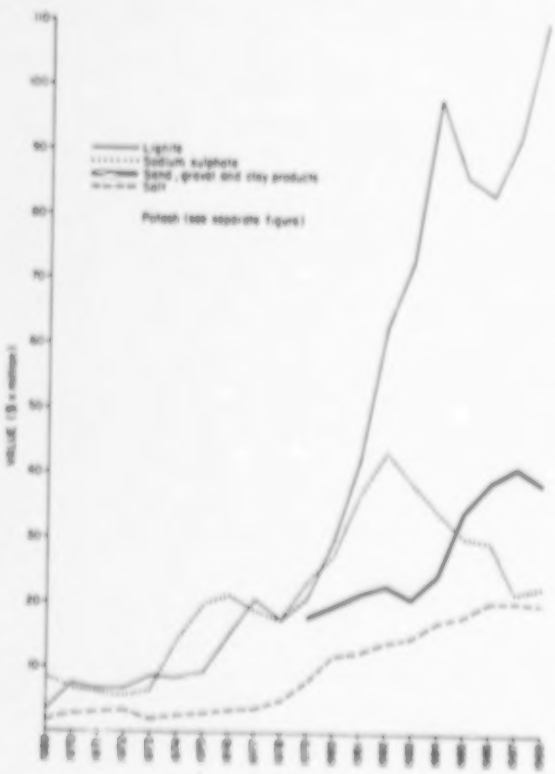


Figure 25 - Value of other industrial mineral production in Saskatchewan from 1969 to 1988.

Plate 12 - Dragline at the Prairie Coal Ltd. Poplar River mine near Coronach.

The first of two 300 MW generating units at the new Shand coal-fired power plant in the Estevan area is expected to come on stream in 1992. The growth in lignite sales is, therefore, assured over the next few years. By 1996 or 1997 annual total sales are expected to be in excess of 13 million tonnes.

Clay

The major ceramic clay-using industries in Saskatchewan are Estevan Brick Ltd. and I-XL Industries Ltd. Products include face and common brick, sewer pipe, and chimney flue linings. Clays for these products are quarried near Estevan, Rockglen, Claybank, Readlyn and Ravenscrag. Pottery clay mined near the community of Ravenscrag from the Upper Cretaceous Whitemud Formation is processed in Medicine Hat, Alberta.

Bentonite from the Upper Cretaceous Bearpaw Formation was quarried by Avonlea Mineral Industries Ltd. near Truax (Plate 13) and processed at Wilcox. Principal uses included drilling mud, animal feed pelletizing, foundry sand binder and as a sealant in civil engineering. Shortly after the company went into receivership in 1990 it was acquired by Canadian Clay Products Inc.

A small quantity of glaciolacustrine clay is produced near Regina and Saskatoon for expanded aggregate production and near Regina for cement production.

Large resources of kaolin have been identified in the Wood Mountain and Eastend - Shaunavon areas (Plate 14). The resource could become the basis for expansion and diversification of the province's clay industry.

Potash

The potash industry in Saskatchewan comprises two solution mines and eight conventional mines supplying about 25 percent of the world potash demand. These deposits are more realistically considered as an integral part of a vast potash-bearing region extending across southern Saskatchewan and into Manitoba, Montana and North Dakota (Figure 26). The mineralized region, however, may be subdivided according to economic potential based on ore grade and preferred mining method (Figure 27).

The ownership of the ten producing potash mines is as follows:

1) Potash Company of America (converted to solution mine)
2) Potash Corporation of Saskatchewan Mining Ltd.
   a)Cory Division
   b)Lanigan Division
   c)Rocanville Division

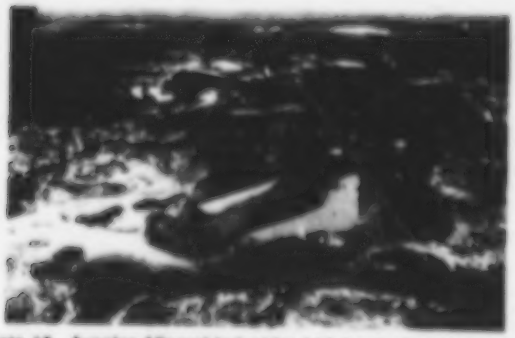


Plate 13 - Avonlea Mineral Industries Ltd. bentonite quarry near Truax (now owned by Canadian Clay Products Inc.).

3) International Minerals and Chemicals Corp. (Canada) Ltd.
   a)K-1
   b)K-2
4) Allan Potash Mines (jointly owned by Potash Corporation of Saskatchewan and TexasGulf Potash Co.)
5) Central Canada Potash
6) Cominco Ltd.
7) Kalium Chemicals Ltd. (Plate 15) (solution mine)

The production capacity of the industry has risen considerably through expansion in the past five or six years and now stands at over 10 million tonnes K_2O equivalent annually. The total value of sales peaked in 1980-81 at slightly over one billion dollars from production of slightly over 7 million tonnes K_2O. By 1986, sales had dropped to approximately 550 million dollars from an estimated production of 6 million tonnes K_2O. The decline is attributed to a surplus in global grain production and a consequent reduction in fertilizer use by the hard-pressed farm industry. By 1988 sales had nearly recovered to the 1980 level.

The Potash Company of America (PCA) mine at Patience Lake was closed due to flooding in 1987. A solution mining pilot test was conducted successfully by about May 1988. The company is now in the final stages of developing a full scale solution mining facility. Natural precipitation of the potash takes place during October-April in surface ponds having a total area of about 50 ha.

Potash Corporation of Saskatchewan continues to operate a 10 tonne per day potassium sulphate pilot plant at Big Quill Lake. The plant operates at about 65 percent capacity and produces a high quality product.

IMC's K-2 mine continues to experience brine inflow which commenced in 1985. The inflow rate appears to have stabilized at about 4546 litres (1000 gal.) per minute. Most of the water is pumped out and disposed of by injection into deeper formations. Inflow is controlled by chemical grouting techniques. Backfilling of some of the old workings is expected to stabilize ground conditions.

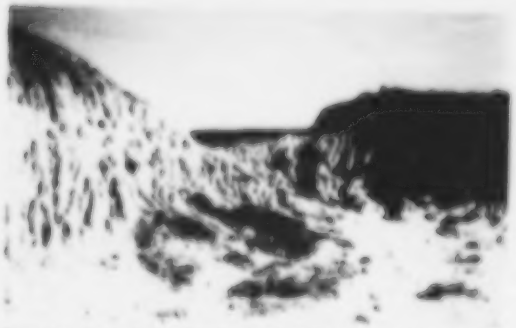


Plate 14 - Kaolinized sand of the Whitemud Formation, Wood Mountain area.

Salt

For practical purposes, salt resources in Saskatchewan may be considered as unlimited. The principal source, and the only one presently exploited, is the thick, massive halite of the extensive potash-bearing Prairie Formation in the southern half of the province.

There are four producers:

1) Sifto Salt Division of Domtar Inc. operating brine wells near Unity;
2) Canadian Salt Co. utilizing waste salt from Kalium Chemicals Ltd. solution potash mine near Belle Plaine;
3) Saskatoon Chemicals Division of Weyerhaeuser conducting a brining operation near Saskatoon; and
4) International Minerals and Chemical Corp. producing byproduct salt from its potash operation near Esterhazy.

Salt and salt-related products include fine vacuum pan salt, bulk chemical salt, livestock salt blocks, fused salt, ice-control salt and salt feedstock for caustic soda, chlorine, sodium hypochlorite, hydrogen and hydrochloric acid.

With minor exceptions, annual salt production has grown steadily in the past 15 years from about 200 000 tonnes to 460 000 tonnes, while value has risen from about $3,000,000 to over $20,000,000.

Sodium Sulphate

The sodium sulphate industry in Saskatchewan comprises four companies operating six deposits. Millar Western Industries produces from Whiteshore Lake northwest of Biggar. Francana Minerals Ltd., a division of Agassiz Resources Ltd., produce from Alsask Lake, Snakehole Lake and Verlo Lake. Saskatchewan Minerals (a division of Dickenson Mines) operates a plant at Chaplin Lake (Plate 16) and at Ingebright Lake near Fox Valley. Two other plants owned by Saskatchewan Minerals (Fredrick Lake near Bishopric and East Sybouts Lake near Gladmar) are presently shut down. The Ormiston Mining and Smelting Co. Ltd. produces from Ormiston Lake, south of Moose Jaw.

Figure 28 - Region of potash mineralization (after Fuzesy, 1982).

Sodium sulphate is extracted by three methods:

1) natural evaporative concentration and crystallization in specially constructed reservoirs;
2) dredging of permanent crystal beds from the lake bottom; and
3) to a lesser extent, solution mining of thick permanent crystal beds.

The mirabilite ($Na_2SO_4.10H_2O$) ore is processed (cleaned and dehydrated) into two types of products based on purity:

1) salt cake (at least 97 percent Na_2SO_4); and
2) detergent grade (at least 99.7 percent Na_2SO_4).

The principal markets for sodium sulphate are the kraft paper industry in western Canada and the international detergent industries. Smaller quantities are used in the glass and textile dye industries.

Operations of the sodium sulphate industry run somewhat countercyclical with respect to the general economy. Competition from byproduct sources of sodium sulphate from the viscose rayon and chrome industries is stronger during economic upturns. The industry is also affected negatively by a declining use of the product in the paper pulp industry. There are also signs that substitutes for sodium sulphate in the detergent industry will also reduce demand.

On the positive side, the Potash Corporation of Saskatchewan has conducted a successful pilot project on the production of potassium sulphate fertilizer using sodium sulphate brine and potash. There is also a potential application for sodium sulphate in coal-fired power plants as a reagent to enhance the efficiency of electrostatic precipitators.

Annual production of anhydrous sodium sulphate peaked in 1974 at over 564 000 tonnes and again in 1981 and 1982 at over 500 000 tonnes. By 1988 the production level declined to about 272 000 tonnes. During the early 1980s the value of sales ranged from about $30 million to nearly $44 million, then declined during the second half of the decade to an average of

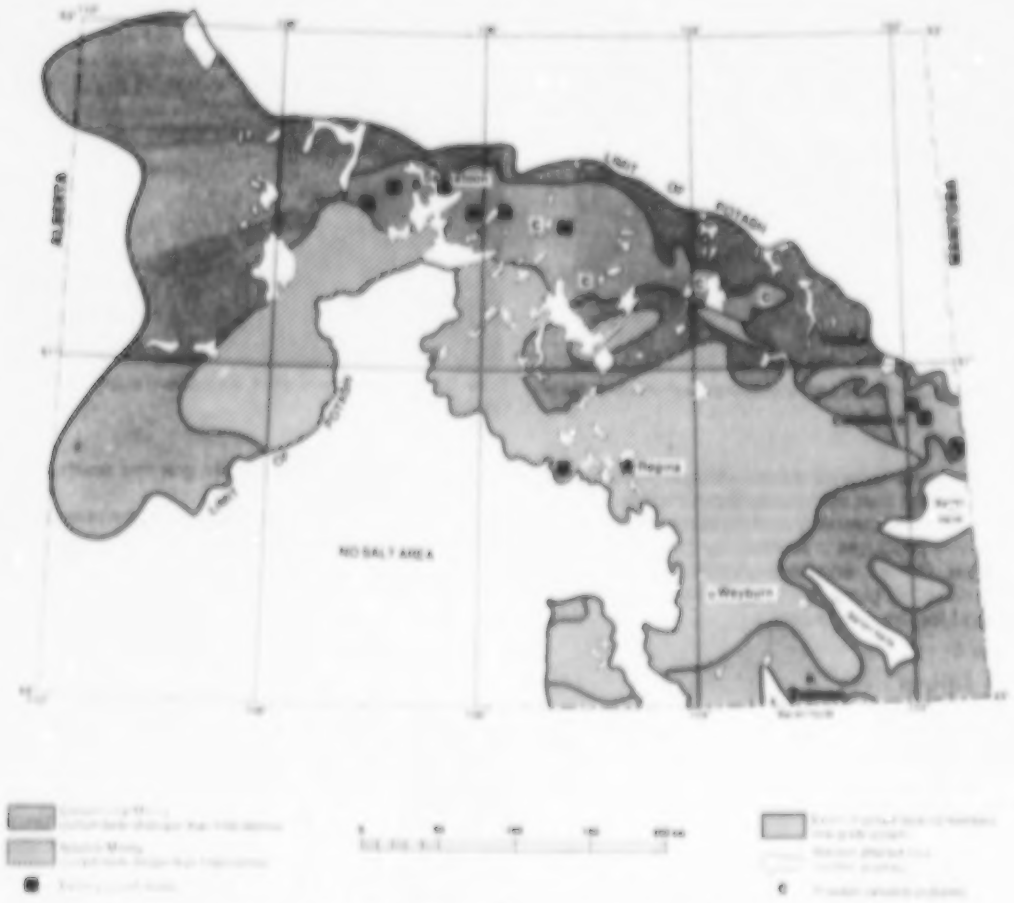


Figure 27 - Economic potential of potash region (after Fuzesy, 1982).

about $24 million. From 1982 to 1990 the average price per tonne varied from about $77 to $95.

Annual capacity of the industry in Saskatchewan is nearly 558 000 tonnes. During 1990 the industry operated at about 55 percent of capacity. The principal negative factor affecting the industry is the declining use in the pulp and paper and detergent industries. Also having an appreciable effect on the market for the natural product is synthetic sodium sulphate production in Canada, which amounted to about 27 000 tonnes in 1989.

Peat

The sole producer of peat moss in the province is Premier Sask. Inc. with production in 1988 and 1989 of over 700,000 bales (about 27 kg each). The source bog is about 100 ha in area and located about 30 km east of Carrot River in east-central Saskatchewan. The plant is situated at Carrot River. Production is by milling and vacuum harvesting. Drying is solar, although occasionally supplemented by artificial drying as needed.

Premier has recently developed a bog immediately north of the plant and an 800 ha bog is in the process of development near Tobin Lake, about 65 km north of the plant. The Tobin Lake bog has a reported thickness of 3.3 m of peat.

Horticultural peat moss is marketed largely in western Canada and the United States to as far away as California and Hawaii.

Industry is presently investigating the potential of fuel peat for power generation in the Canoe Lake area.

Silica Sand

Silica sand has been quarried in Saskatchewan since the thirties, primarily as a smelter flux for the Hudson Bay Mining and Smelting Co. Ltd. copper-zinc plant at Flin Flon. The high-grade Lower Cretaceous silica sand deposits along the Red Deer River northeast of Hudson Bay have been explored and evaluated periodically.

Plate 15 - Kalium Chemicals Ltd. solution potash mine at Belle Plaine.

Plate 16 - Saskatchewan Minerals sodium sulphate plant at Chaplin Lake.

Red Deer Silica Inc. recently constructed an access road to the deposit and commenced production. The company erected a screening and washing facility at the quarry and now produces a product for the golf course bunker market. Other market opportunities are being investigated, including glass, foundry, filtration, silicon, and frac sand for the oil industry.

Building Stone

Although Saskatchewan is one of the few provinces without a stone quarrying industry, it has potential sources of stone in the Creighton-Deschambault Lake area and the La Ronge region.

Dolomites of the Ordovician Red River Formation in the vicinity of Limestone Lake are best known through recent studies carried out under the Canada-Saskatchewan Mineral Development Agreement of 1984. The quality of the stone appears to be adequate for application as rubble stone in a random setting or as dry pack. Dolomite quarrying was undertaken in 1989 in the Deschambault Lake area by Graham Construction and Engineering (1985) Ltd. specifically for construction of the Agricultural Building at the University of Saskatchewan in Saskatoon.

In the Amisk Lake area the Ordovician dolomites are less fractured and it is possible to quarry substantially larger blocks. Depending on the average block size and waste factor the deposits could gain prominence in North American markets. The dolomite is very hard, dense and takes a very good polish. It is classed as a dolomite marble in the stone industry.

Rocks of the Saskatchewan Precambrian Shield are attracting industry attention. Preliminary resource evaluations conducted in the La Ronge, Pelican Narrows and Creighton areas have revealed several promising deposits:

a) black to dark charcoal gray diorite near Neyrinck Lake (La Ronge Domain)
b) white-veined amphibolite reminiscent of verde antique near Mystic Lake
c) dark green and red gneissic granites south of Pelican Narrows
d) black and white regularly banded gneisses and contorted, augen-ized gneisses in the Jan Lake and Maligne Lake area that have potential as specialty ornamental stone.

Magnesium

Large resources of carnallite ($KCl.MgCl_2.6H_2O$) are associated with the three potash-bearing members of the Devonian Prairie Formation, which tend to be carnallitic toward their margins. Grades of up to 80 percent carnallite are known south and southwest of the Quill Lakes area. Fuzesy (1982) has reported carnallite-rich beds, probably of considerable areal extent, at Moose Mountain, Parkerview, Foam Lake, Nokomis, Wilkie and east of Watrous.

Other potential sources of magnesium include some of the saline lakes, such as Big Quill, Redberry, Basin, Little Manitou, Muskiki and Aroma. Magnesium content in

Figure 28 - Subsurface brine occurrences in Saskatchewan.

the brines ranges from 0.157 to 2.3 percent. Subsurface brines, particularly from the Winnipegosis, Dawson Bay, and Souris River Formations, are extremely rich in magnesium chloride and calcium chloride. Magnesium values range from about 11 000 mg/l to 51 000 mg/l and calcium from 32 000 mg/l to over 119 000 mg/l (Figure 28). Calcium chloride brine occurring as mine seepage is produced at the PCS Cory potash mine near Saskatoon.

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